POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science

Computer Science and Engineering

TANGIBLE MIXED REALITY FOR PEOPLE WITH NEURODEVELOPMENTAL DISORDERS

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Academic Year 2018/2019

Sommario

I disturbi del neuro-sviluppo (Neurodevelopmental disorders - NDD) sono patologie che si manifestano nelle prime fasi dello sviluppo di un individuo e che ne limitano le capacità personali, cognitive e motorie.

Lo scopo di questa tesi è di esplorare il potenziale della *Tangible Mixed Reality (TMR)* per aiutare i soggetti affetti da queste patologie. Con questo termine si intende una tipologia di Mixed Reality (MR) che include l'interazione tra dispositivi per la realtà mista ed oggetti "intelligenti" (Smart Objects) con feedback tangibili.

Questo innovativo paradigma di interazione è stato istanziato in un'applicazione denominata *Along the Oceanic Flow (ATOF)*. L'applicazione è stata progettata per supportare terapisti esperti nel campo dei disturbi del neuro-sviluppo, ed ha l'obiettivo di aiutare i soggetti affetti da queste patologie a migliorare le proprie abilità motorie e cognitive mediante esercizi presentati sottoforma di gioco. *ATOF* trasforma la stanza dell'utente in un fondale oceanico ricco di decorazioni interattive in cui il soggetto, sfruttando il paradigma TMR, deve completare diverse esperienze eseguendo compiti cognitivi e motori quali collezionare elementi, evitare ostacoli e trovare modi per aprire scrigni del tesoro.

Le attività da svolgere sono state pensate in modo da essere completate facilmente e, tra queste, è anche presente un'esperienza in cui la difficoltà degli esercizi aumenta gradatamente durante il gioco. Inoltre, tutte le esperienze possono essere personalizzate dal terapista in modo da soddisfare le specifiche esigenze di ogni utente-paziente, dato che ognuno di essi avrà un diverso grado di invalidità.

Uno studio esplorativo che ha coinvolto 14 soggetti affetti da NDD è stato eseguito per investigare il gradimento e l'usabilità di *ATOF*, così come il suo potenziale come strumento terapeutico.

L'applicazione è stata ben accettata dai partecipanti e le attività nello spazio *TMR* sono state percepite come gradevoli e semplici. È necessaria una più ampia ricerca empirica e a lungo termine per convalidare questi primi risultati. Tuttavia, lo studio empirico suggerisce che l'applicazione *ATOF*, e più in generale le applicazioni basate sul paradigma TMR, potrebbero essere adottate come complemento ad interventi più tradizionali.

Questo lavoro, i problemi incontrati e le soluzioni implementate, potrebbero essere di ispirazione per progettisti e sviluppatori di future applicazioni TMR dedicate a persone affette da NDD, così come altri gruppi di utenti con diverse forme di disabilità cognitive.

Abstract

Neurodevelopmental disorders (NDD) are pathologies that can appear in child's early developmental process, limiting personal, cognitive and motor capabilities.

The purpose of this thesis is to explore the potential of the *Tangible Mixed Reality (TMR)* in helping subjects affected by those pathologies. This term refers to a type of *Mixed Reality (MR)* including the interaction between *MR* devices and *Smart Objects* with tangible feedbacks.

This innovative interaction paradigm has been instantiated in an application called *Along the Oceanic Flow (ATOF)*. This application is designed to support NDD experts and has the goal to help people affected by NDD to improve motor and cognitive skills through game exercises. *ATOF* transforms the user's room into an ocean floor full of interactive decorations in which the subject, leveraging the TMR interaction paradigm, has to complete different experiences by doing motor and cognitive tasks like collecting elements, avoiding obstacles and finding ways to open treasure chests.

The tasks have been thought to be very easy to complete and, among them, there is an experience in which the difficulty of the exercises gradually increases during the game. Furthermore, all the experiences can be customized by the therapist in order to satisfy the specific needs of each user-patient, given the fact that each one of them will have a different degree of disability.

An exploratory study involving 14 subjects affected by NDD has been performed to investigate the *likability* and *usability* of *Along the Oceanic Flow* and its potential as a therapeutic tool.

ATOF was well-accepted by the participants and the activities in the *TMR* space were perceived as enjoyable and simple. A more extensive and long-term empirical research is needed to validate these early results, but the study suggests that *ATOF*, and more generally the applications based on the *TMR* paradigm, could be adopted as a complement to more traditional interventions.

This work, the problems encountered, and the solutions implemented, could be inspirational for the designers and developers of future TMR applications dedicated to people affected by NDD and not only.

Ringraziamenti

Viaggiare mi piace, quindi viaggio indietro nel tempo fino al momento in cui ho iniziato questo percorso. Riaffiorano i ricordi delle sfide, delle difficoltà e degli sforzi nel capire quale fosse davvero la mia strada.

Intraprendere questo cammino è stato come scalare una montagna, ma da quassù la vista è bellissima.

Ogni volta che guardo al passato capisco che il supporto di mia madre, mio padre e mio fratello Alessandro sono stati fondamentali. Devo ricordare loro che sono i genitori e il fratello migliori che mi potessero capitare, mi hanno permesso di arrivare sin dove sono e mi hanno aiutato ad affrontare qualsiasi tipo di difficoltà. Grazie.

Un grazie immenso (come lui) anche al mio amico storico, Matteo, che qualsiasi cosa succeda è sempre presente. Glielo dovrebbero spiegare, ai bambini, che è l'infanzia il periodo migliore in cui fare amicizie che durano più di una vita.

Un grazie speciale a Laura, con cui ho condiviso viaggi, pensieri e speranze. Riesce sempre a tirare fuori qualche lato del mio carattere che non credevo nemmeno di avere. Grazie perché mi sai ascoltare. Non vedo l'ora di vederti raggiungere i tuoi obiettivi.

Un ringraziamento particolare ai miei cari amici appassionati di musica, Fabiana e Matia, che mi hanno incoraggiato a dare il meglio di me e con cui non vedo l'ora di tornare a comporre. Devo ringraziare anche la musica, amica importante nelle situazioni difficili.

Grazie a mio cugino Marco, Matteo, Eric, Siria e tutti gli amici protagonisti di serate indimenticabili. Con la vostra simpatia riuscite a migliorare qualunque giornata.

Grazie anche a tutti gli amici incontrati in università, che mi hanno accompagnato durante questo viaggio, rendendolo migliore. Credo che il vero scopo dell'università sia offrire la possibilità di trovare persone come voi.

Un profondo ringraziamento va alla Professoressa Garzotto, che mi ha permesso di approfondire la mia grande passione per la Mixed Reality e tutto il settore XR. Grazie per questa opportunità, per l'incoraggiamento e per le parole di stima.

Un grande ringraziamento ai miei correlatori, Francesco ed Eleonora. Grazie per i vostri consigli, la vostra disponibilità e la vostra simpatia. Grazie anche a Emanuele e ai ragazzi dell'I3Lab per il supporto e il tempo passato insieme. Un grande saluto anche a tutti i ragazzi e gli educatori della cooperativa *Fraternità e Amicizia*, è stata una bellissima esperienza e un'occasione per scoprire un mondo pieno di altruismo.

Un caro saluto infine anche a tutti quelli che ho dimenticato, o che mi hanno dimenticato.

Casomai non vi rivedessi, buon pomeriggio, buonasera e buonanotte!

Christian

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1 Introduction

1.1 Tangible Mixed Reality

Tangible Mixed Reality (TMR) is a new interaction paradigm that leverages the interoperability between *Mixed Reality* devices and *Smart Objects* with tangible feedbacks. This experimental approach arises from the effort to break down the barriers between the virtual and the real world, blending them and enriching the mixture with the intuitive manipulation and interaction of physical objects.

On one side of the *TMR* metaphor there is the *Mixed Reality (MR)*. This is a computer-based technology offering three-dimensional real-time mixed experiences, which can be used to augment the surrounding environment with world-anchored virtual interactive elements, called holograms. These experiences are presented in a way that the user of a MR application maintains the contact with the reality and can explore and interact with virtual entities inside his/her own decorated room. MR is often associated with Augmented Reality (AR) and Virtual Reality (VR) because they exploit the same type of technology, but there are some important differences to point out. Augmented Reality just overlays virtual objects on the real-world environment without anchoring them, and Virtual Reality immerses the user in a fully artificial digital environment. Mixed Reality, instead, is defined as *"anywhere between the extrema of the virtuality continuum"* [59], where the *virtuality continuum* extends from the completely real through to the completely virtual environment, therefore including both AR and VR at its extremes. Nowadays, MR devices are still in an experimental phase, therefore they can leverage just a portion of the *virtuality continuum*, and they provide something more than the richest form of AR. However, future technology progresses will expand the portion of the *virtuality continuum* exploited by those devices. In this last year two Mixed Reality devices aroused particular attraction, Microsoft HoloLens [50] and Magic Leap One [43], and some other companies are planning to release their device in the next future [12][20]. The application fields in which Mixed Reality is being used is increasing and include military [74][81], industrial field [9], and remote working [71], but also healthcare and disabilities, as some recent studies demonstrate [4][5]. In Figure 1.1 some examples of MR and TMR are shown.

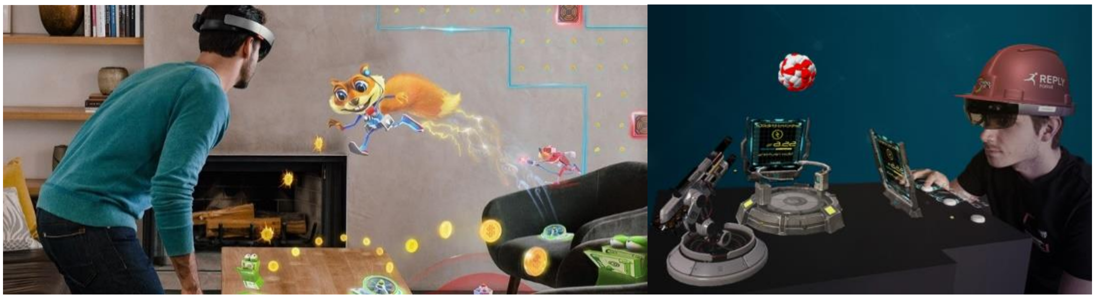


Figure 1.1: examples of MR (left) and TMR with smart buttons (right)

On the other side of the *TMR* metaphor there are the *Smart Objects*. They are intercommunicating objects with electronic devices inside capable of controlling their reaction as a consequence of external interactions. They can enhance the interaction with other objects or people, in fact sometimes they are also referred to with the term *Tangible User Interfaces* [35][39]. *Smart Objects* can be used in various fields like domotics, clothing and security [82], but a particularly interesting subset of these smart objects are smart toys with animal features (Figure 1.2), used for an approach similar to Pet Therapy, whose efficacy in rehabilitation and disabilities contexts has been confirmed by some studies [2][13][29].

Figure 1.2: examples of Smart Objects developed at the I3Lab: Dolphin Sam and Paro

As a result it can be noticed an increasing popularity of both MR technology and Smart Objects in various domains that range from gaming and entertainment[75], to learning, professional training, therapy and rehabilitation [4][5].

1.2 Neurodevelopmental Disorders

NDD are a group of disabilities appearing during the developmental period and are mostly characterized by severe deficits in the mental and cognitive areas that produce severe personal, social, physical and motor difficulties.

Therapies for people with Neurodevelopmental Disorders (NDD) is one of the fields in which the Mixed Reality technology has recently been applied [4][5].

Those disorders are various and unfortunately can co-exist. Some main examples are Intellectual Disability, Autistic Spectrum Disorder (ASD) and Motor disorders (including also developmental coordination disorder [83] and stereotypic movement disorder [46]) that can cause abnormal and involuntary movements due to damage to the nervous system [40].

Other examples include also Attention Deficit Hyperactivity Disorder, Communication disorders and Specific Learning Disorders.

Recent studies suggest that NDD pathologies are becoming more and more frequent among people. For example, both the ADDM (Autism and Developmental Disabilities Monitoring Network) and the IHME (Institute for Health Metrics and Evaluation) assert that in 2016 about 1 of 100 children in the world has been identified with ASD [61][63]. In Figure 1.3 it can be seen a worldwide overview of the ASD diffusion, while in Figure 1.4 it is shown its increment over the years.

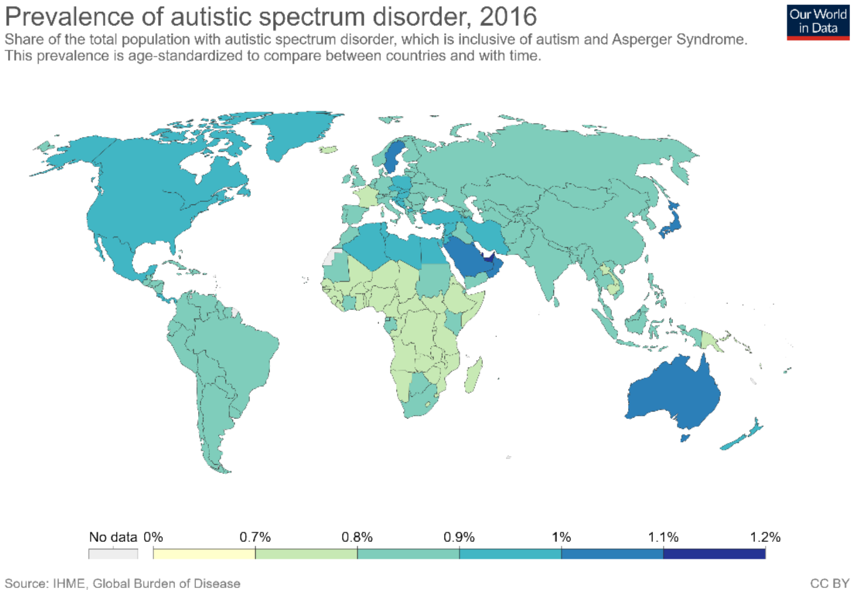


Figure 1.3: worldwide overview of ASD, year 2016

These data have been confirmed also by the recent European project ASDEU (Autism Spectrum Disorder in European Union) that included even specific data about diffusion of ASD in Italy [6]. This increase of ASD cases has been partly explained as a result of changes in diagnosis and classification criteria but is not yet completely understood. In the meanwhile, new types of solutions are needed to tackle this problem.

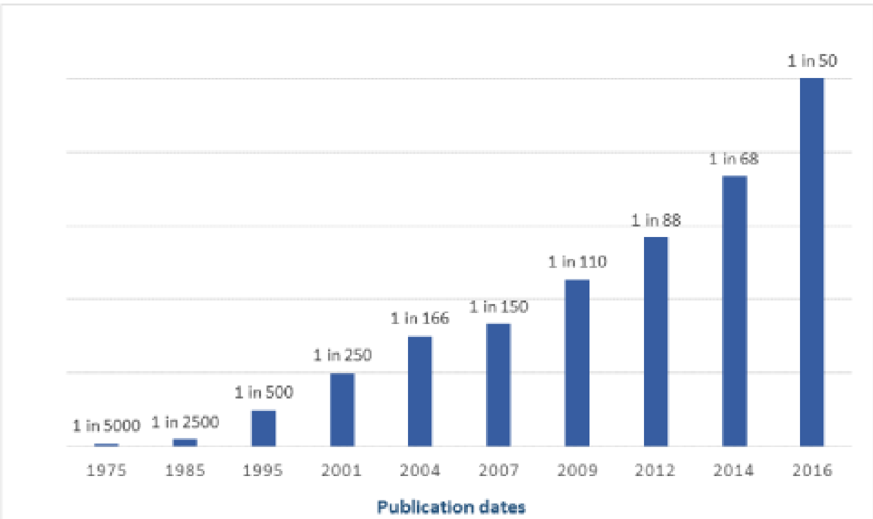


Figure 1.4: increment of ASD diagnosis over time

Symptoms shown by people with this type of disabilities include difficulties in social interactions and atypical communication skills, but also motor [60], postural and coordination impairments [23].

1.3 Thesis contribution

The main purpose of this thesis has been to explore the potential of the combination of these two technologies, Mixed Reality and Smart Objects, in the attempt to improve NDD people conditions. The motivation arose from the fact that, as previously said, both of those technologies have separately shown possible benefits in educational and therapeutic practices in the NDD field [5][13].

Along the Oceanic Flow (ATOF), the application born from this research, transforms the user's room into an ocean floor full of interactive decorations. The user-patient has to complete some motor and cognitive tasks, specifically designed for NDD people, leveraging the innovative TMR interaction paradigm.

Three possible experiences are offered by *ATOF*, including some completely customizable by the therapist in order to satisfy the specific needs of each patient. As Figure 1.6 shows, these experiences involve the user-patient in leveraging a dolphin Smart Toy to collect virtual elements like bubble rings flowing in the room, as well as avoiding obstacles and other motor tasks. In one of the experiences it is also included a treasure hunt game where the user, exploiting cognitive abilities, has to find a way to open a treasure chest placed around the room.

The application has gone through an iterative development cycle depicted in Figure 1.5. An analysis of the user needs started the process, which continued with the requirements gathering, design and prototyping. After that, an empirical evaluation led to a redefinition of some requirements and design choices in order to suit users' needs as much as possible.

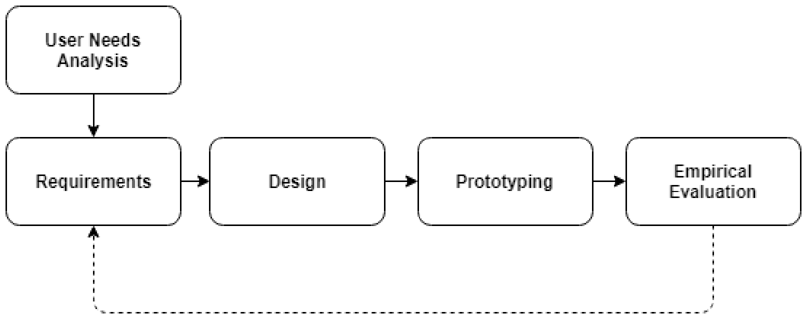


Figure 1.5: ATOF iterative development cycle

The value proposition of *ATOF* arises from the fact that it offers experiences that can't be replicated in the real world, thus trying to give to NDD users and therapists an innovative system, leveraging an innovative interaction paradigm, that could be used as a complement of more traditional therapies.

The exploratory study involving subjects with NDD has been performed to assess its *likability* and *usability*, as well as its potential as a therapeutic tool. The results reported that *ATOF* has been well-accepted by the participants and the activities in the *TMR* space have been perceived as enjoyable.

Figure 1.6: Along the Oceanic Flow, preview

1.4 Thesis structure

The thesis is structured as follows:

- In chapter 2 the state of the art about XR is presented. There are described the modern technologies that can help people with NDD in mitigating symptoms related to their condition. In particular are deeply examined previous researches and works in the contexts of XR (VR, AR, MR) and Smart Objects. Then some types of Head Mounted Displays (HMDs) are technically analysed and compared regarding their potential usage in the NDD field.
- In chapter 3 the needs, goals and requirements of the application are described. Firstly are presented the main target groups that have been considered and their needs. Then goals, requirements and constraints of the system are described in detail.
- In chapter 4 we find the design of the application. A high-level description of the system is presented and every component is described in detail, as well as their evolution during the research. Finally, there are some example scenarios and a discussion about the user experience.
- In chapter 5 the system is described from a technological and implementative point of view. Tools and software used to build the application are presented, along with the necessary hardware components. Then the software architecture of the entire system is described in detail, as well as the problems found and their respective solutions.
- In chapter 6 are described in depth the two experimentations done with the NDD users that took place at a therapeutic center in order to assess and validate the application. All the information and feedbacks gathered to improve the application are then reported. Finally, an analysis of the results of the assessment is done.
- In chapter 7 are discussed the conclusions about the research and the suggestions about possible future works on this topic.
- In chapter 8 are listed all the references, alphabetically ordered.

2 State of the art

The contexts in which technology can be used are countless, and its usage is particularly important in the therapeutic field, where it can help patients having different pathologies. Among those patients, there are subjects with Neurodevelopmental Disorders (NDD). Therapists in this field are always seeking new therapeutic solutions, and therapeutic centers are adopting more frequently new technologies to improve their activities for these subjects, aimed at developing their motor, cognitive and social skills.

One of the most interesting technologies for the NDD field is indeed the wearable one. Wearable technology consists in smart electronic devices (electronic device with micro-controllers) that can be incorporated into clothing or worn on the body as implants or accessories. The usage of wearable technology has increased a lot in the last decade, and the forecasts say it will continue growing [21].

Usability and accessibility play an important role in the NDD field, and wearable technology can help with these necessities. In fact, wearable devices, as they improve, can help letting technology become more and more comfortable and "invisible" to the user (as theorized in ubiquitous computing [84]), which in case of users with impairments is an important point to consider in order to make a therapy really effective.

Some examples of wearable technologies are fitness bands [18], smartwatches [3] and headsets [62]. Among headsets there are lot of devices related to virtual and augmented reality, including solutions ranging between these two worlds. One of the devices that is recently gaining lot of attraction is Microsoft Hololens [50]. This device is capable to mix the real world with virtual interactive entities, an approach called "Mixed Reality".

2.1 Virtual, Augmented and Mixed Reality for NDD people

The definitions in the modern contemporary industry makes a clear distinction between VR, AR and MR:

- **Virtual reality (VR)** immerses users in a fully artificial digital environment.
- **Augmented reality (AR)** overlays virtual objects on the real-world environment.
- **Mixed reality (MR)** not just overlays but *anchors* virtual objects to the real world and allows the user to *interact* with the virtual objects in a much more effective way.

In particular, in a 1994 paper by Paul Milgram and Fumio Kishino, *Mixed Reality* is defined as "anywhere between the extrema of the virtuality continuum"[59], where the ***virtuality continuum*** extends from the completely real through to the completely virtual environment. In Figure 2.1 it is shown the concept.

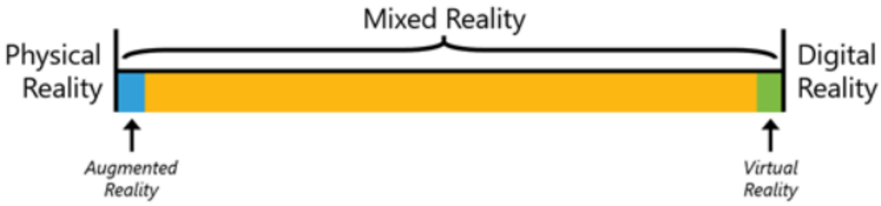


Figure 2.1: The virtuality continuum.

Since then, some other additional terms have been used to represent just particular facets of the *virtuality continuum*, like *Immersive Virtual Reality* (virtual reality with a more effective interaction) and *Augmented Virtuality* (predominant virtual reality merged with just a few objects of the real world). These two specific implementations are placed closer to digital reality.

Mixed Reality (MR), is the approach with which real and virtual worlds are merged, producing new environments and visualizations where physical and digital objects co-exist and interact in real time [17].

It is made possible by advancements in computer vision, graphical processing power, display technology and input systems.

The first mixed reality system was developed at the US Air Force's Armstrong Laboratories in the early 1990s. In two studies [67][68] published in 1992 and 1993 this project demonstrated for the first time that human performance could be significantly amplified by the introduction of spatially registered virtual objects overlaid on top of a person's direct view of a real physical environment. These studies [67][68] focused especially on applications in the military field, but they opened the way for the possibility that this technology could also be applied with success in a lot of other fields, including healthcare, accessibility and disabilities.

The term *Mixed Reality* was originally introduced a bit later, in the previously mentioned 1994 paper by Paul Milgram and Fumio Kishino, "A Taxonomy of Mixed Reality Visual Displays" [59]. Their paper introduced the concept of the *virtuality continuum* and focused on categorization of displays. Then, the application of *Mixed Reality* started including also environmental input, spatial sound and location.

[Since now on, the term XR will be used for considerations regarding VR, AR and MR.]

Applications and examples

Both MR and VR, as mentioned before, have been used in lot of fields. In particular, researches of the medical care sector see a great potential of these technologies that have been used in many ways. Some examples are psychiatric care [25], educational tools for therapists [7], schizophrenia [24] and rehabilitation programs [16].

In the last years there have been more research studies in the VR field with respect to MR, since manufacturing and implementation of VR headset solutions is easier than MR one, not having to consider the integration with the environment. So, there wasn't a real comparison between the two approaches.

However, the situation is rapidly changing due to technology progress, in fact lot of fields involving MR are emerging. Apart of the military sector already mentioned there are also simulation based learning, remote working (improving autonomy and efficiency of workers [71]) and even recent researches in the consciousness topic (regarding the transfer of human consciousness in a digital form leveraging blockchains [1][72]).

This suggests that the application of mixed reality to the intellectual disability field is now affordable, possible and potentially very effective, as previously anticipated. In fact, there are already some preliminary research studies regarding the application of MR to Neurodevelopmental disorders [4][5], therefore a comparison between various XR approaches for the NDD field seems a good point to start with.

Among the XR approaches that have been already used with success to specifically treat intellectual disabilities there is the Virtual reality (VR), that is becoming way more effective and accessible in these last years due to its technology improvement and rise in the consumers market with cheaper products.

Reading previous researches, it can be noticed that the ways in which VR has been used to treat NDD are manifold, some recent examples are:

- **XOOM**, a web based software platform that allows creating web-based applications of wearable immersive virtual reality (WIVR) that leverage 360° realistic storytelling videos as interactive virtual tours in order to improve attentional skills and cause-understanding capabilities in subjects with NDD [26][44].
- **Social MatchUP**, a multiplayer cooperative Virtual Reality game for children with NDD that uses a shared virtual environment to let users improve their social and collaborative skills. The participants can see each other in the virtual environment as virtual avatars and have to complete a memory-based game, that also improves concentration abilities [42].
- **Wildcard:** a collection of some simple games using wearable immersive virtual reality (WIVR) and cheap head mounted displays (like Google Cardboard) to promote concentration through gaze focus and direction [27].
- **Jazzy:** a VR application for users with Amblyopia that exploits visual layers to display different contents for each eye on the Head Mounted Display (HMD) screens. This system allows users train hand-eye coordination skills in a more lifelike and engaging way compared to traditional methods [70].

A preview of these applications can be seen in Figure 2.2.

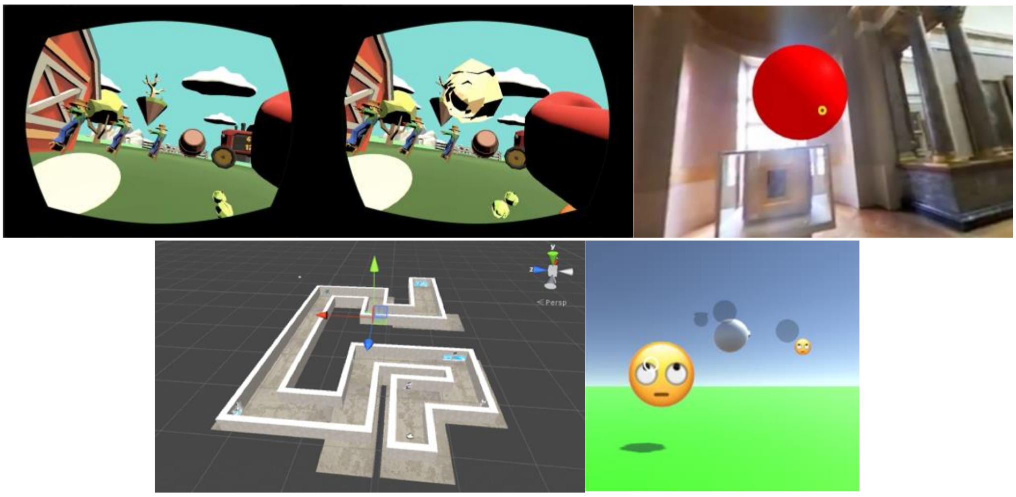


Figure 2.2: From up-left: Jazzy (two different images displayed for each eye), XOOM (interactive 360 degrees VR video), Wildcard (the user moves through the labyrinth focusing on walls), Social Matchup (players, through virtual avatars, must point simultaneously pairs of the same object).

As it can be deduced, the usage of VR (including WIVR) promotes attention and engagement by eliminating distraction coming from external visual stimuli, that for some NDD users is an obstacle [36]. As a starting point this is an effective approach.

However, in the long term a progressive introduction of external stimuli could be preferable, in order to help users with NDD improve constantly and get used to obstacles and difficulties they face every day in the real world. As a matter of fact, the aim is that people with intellectual disabilities also improve in dealing with external distractions in the best possible way.

It is natural to think that, in order to obtain this progressive introduction of external stimuli, a Virtual Reality headset is not anymore the best appropriate solution for all the contexts (maybe a good complementary one, considering the alternatives), because this type of device is conceived to isolate the user from the external world in a fixed way. It is true that the virtual environments in VR can be made somehow a bit more realistic (depending on the hardware capabilities of the headset), but still the real world surrounding the user is completely occluded by the device and is not really part of the experience.

Therefore, there is the need for a headset and a technology capable to customize the level of involvement depending on the necessities of the user. That's here where the Mixed Reality can make the difference.

Mixed Reality, in fact, being an XR approach enclosing a bigger portion of the *virtuality continuum* between AR and VR, allows to customize the degree of blending between virtual and real world in a very effective way, ranging from simple AR experiences to much more merged ones. Mixed Reality devices are also spatial aware, meaning that they are capable to understand and reconstruct digitally the room where they are placed, if needed.

These aspects allow to use these new devices in different and various contexts for NDD people and to personalize the treatment depending on the user.

Furthermore, Mixed Reality for some users it is even a necessity because, depending on the pathology, they could need to maintain a contact with reality to avoid confusion or being scared by too much immersivity.

The technology supporting Mixed Reality is more recent and experimental than the one related to Virtual Reality, nevertheless in the last two years there have been great steps in this field and the potential of this approach is very high. **Microsoft Hololens** is the best device, at the moment, capable of managing Mixed Reality (later it will be shown why).

Recent research studies show that Mixed Reality can help people with NDD in improving some of their cognitive skills. Some example applications used for these studies are:

- **HoloLearn** [5], a system that helps people with NDD learn how to perform simple everyday tasks in domestic environments, improving autonomy.
- **MemHolo** [4], a solution that helps elderly people with Alzheimer's Disease practice short-term and spatial memory skills in a safe and controlled mixed reality environment.

A preview of those applications can be seen in Figure 2.3.

Figure 2.3: Hololearn (lay the table), MemHolo (finding pairs)

Mixed Reality devices could have a much broader potential, especially in therapeutic contest, being completely customizable experience devices. Furtherly, mixed reality suffers less from the motion sickness problem (misalignment between the movement perceived by the eyesight and the one perceived by the vestibular apparatus) because the user maintains a connection with the real world, therefore he/she has got lot of steady reference objects.

In the case of HoloLens, another point in favour is that it is a standalone independent solution integrating all the needed hardware components in one headset designed to be comfortable, while many VR devices are dependant from smartphones or computers. Plus, it can be worn with glasses, a requirement very important for some patients that most of VR devices don't satisfy at all due to their nature.

Mixed Reality could be a window to the future of NDD therapies thanks to all these aspects, therefore the most natural and effective thing to do was to focus on it for this research.

2.2 Smart Objects for NDD people

Another example of technological tools used for people with NDD are Smart Objects.

Smart objects are objects with electronic devices inside capable of controlling their reaction as a consequence of external interactions. Robots, smart lights and smart plugs are an example.

It’s a very broad category of independent intercommunicating objects that makes it possible to talk about internet of things (IOT), but a subset of these smart objects interesting for the NDD use case is the one including smart toys used for an approach similar to *Pet Therapy*.

In fact, *Pet Therapy* is a type of treatment that leverages animals to develop a physical and affective relation in order to improve patient’s conditions along with more traditional therapies. Various studies proved that this treatment is useful in psychological, educational and motor rehabilitation contexts [8].

Most of the effectiveness of this method is based on triggering a strong emotive relation and a psychological stimulus capable to influence social behaviours of the patient [48]. Along with the *Pet Therapy* there is also the more specific *Dolphin Therapy*, that researches proved to be a very effective form [11][31] of *Pet Therapy* capable to increase cognitive, verbal and motor capabilities [69].

These are enough reasons to wonder if Smart Objects (or better, Smart Toys) resembling pets could be used with success in treatment of neurodevelopmental disorders. Previous research demonstrated that robots and Smart Toys can indeed help children with NDD in socializing with others and improving some cognitive skills like attention [2][29].

Figure 2.4: Teo, Paro, Dolphin Sam

Some examples of Smart Toys developed for children with NDD are Teo, Paro and the Dolphin Sam [13]. They can be seen in Figure 2.4.

Due to the effectiveness of *Dolphin Therapy* mentioned above, the interest of this research focused on the Dolphin Sam.

2.3 Tangible MR

As previously said, both *Mixed Reality* and *Smart Objects* have been separately used with success in therapies for people with NDD or some other pathologies.

Therefore, it is natural to wonder if there could be an improvement in therapies using the two technologies in tandem inside the same application.

This approach entails a strict connection between digital world and real world. In literature there have been discussed some theories and solutions with this modus operandi, in particular:

- There have been analysed various levels of interaction between the physical and the virtual world, where there is a progressive transition from pure real to pure virtual experiences. It is reached the point where users can physically touch objects they are observing virtually, with a mapping one-to-one; or it is even possible to reach body decoupling interaction level, where there isn't any link to the physical world [37].
- It has been discussed for a long time the ubiquitous computing paradigm "*UbiComp*" (theorized the first time by Mark Weiser in 1991) where everyday objects act as interfaces [84]
- There have been experimented various solutions. An example has been a framework to enable users to interact with complex machinery via hologram-based interaction and nearby smart devices [15]. Another example is a teaching app made by Forge-Reply explaining the nuclear fission where the user has to press physical smart buttons to trigger chemical reactions (Figure 2.5) [22]. Playful environments using mixed reality have also been explored [85].

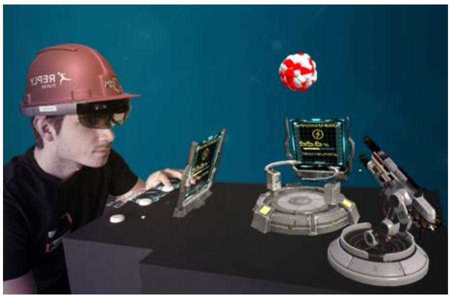


Figure 2.5: Holo Nuclear Fission, by Forge-Reply

However, a thorough search of the relevant literature yielded that none of these *Mixed Reality* solutions have been yet applied in tandem with *Smart Objects* to treat NDD and similar pathologies.

The therapeutic potential of the combination of those two technologies is high since both of them have been separately used with success to treat NDD. In addition, having Smart Objects inside the treatment keep a strong connection with the real world that can help some users.

Therefore, due to these manifold positive and promising aspects, both *Mixed Reality* and *Smart Objects* have been used for this research. This solution contributes to the creation of a new interaction paradigm, commonly called "**Tangible Mixed Reality**".

Tangible Mixed Reality for NDD

Tangible Mixed Reality (TMR) is a relatively new term defining this new approach, however some preliminary solutions and researches bringing specifically this name (or a very similar one) have already been conducted over this topic. Some of them include the usage of smart objects like some solutions seen in the previous paragraph, while others simply try to use real objects as interfaces:

- It has been experimented a solution for augmenting virtual objects with physical objects using a mixed reality headset and a physical support attached to the human body capable to simulate interaction. The usage scenarios of this solution included collaborative works in automotive and interior design fields. Further studies will be done by researchers with mini drones instead of the physical support [73].
- There have been developed some systems that opportunistically annex physical objects from a user's current physical environment to provide the best-available haptic sensation for virtual objects. Those systems continuously scans user's surrounding, selects physical objects that are similar to given virtual objects, and overlays the virtual models on to selected physical ones reducing the visual-haptic mismatch [14][33]. A similar system instead combined Mixed Reality and capacitive 3D printed objects that can be sensed on an interactive surface to enable remote interaction while providing the same tangible experience as in co-located scenarios [32].
- There also have been discussed some design guidelines for Tangible Mixed Reality interfaces, including studies over marker-based and markerless tracking of real objects, solutions considered similar to interacting with a tangible interface [10].

As it can be seen, the usage of smart objects in the *Tangible Mixed Reality* paradigm has not yet been fully explored, and the application to NDD field is still completely experimental in this case, but promising. This gave a huge motivation to the author of this thesis in designing a solution leveraging all those aspects.

For this work it has been used the *Dolphin Smart Object*, as already mentioned, and it has been necessary to choose between various MR headset solutions. Considering all the positive and negative aspects, it has been chosen *Microsoft Hololens* for this research. The motivations are explained in the next section.

2.4 Wearable MR Solutions

In this section is presented an overview of the available and future Head Mounted Displays (HMD) solutions dedicated to the Mixed Reality, as well as a comparison regarding their application to the NDD field.

Considering all the motivations mentioned in the previous chapters, this research has focused on *see-through displays*. They allow users to maintain contact with the physical environment and they are capable to customize the blending between real and virtual world.

There are not many solutions but this is due to the fact that Mixed Reality HMDs are very innovative and experimental therefore at the moment they need much more time for being manufactured and developed with respect to other products.

2.4.1 Magic Leap One

Figure 2.6: Magic Leap One

Magic Leap is an American start-up company working on a HMD retinal display called *Magic Leap One*. It was founded in 2010 and has raised billions from a list of investors including Google, that after Google Glass apparent failure (Google Glass was an HMD for augmented reality) seems to be more interested in this Mixed Reality headset.

This headset superimposes 3D computer-generated imagery over real world objects, by projecting a digital light field into the user's eye retina[41]. Before Magic Leap, a HMD using a similar light field technique had been demonstrated by Nvidia in 2013. However Magic Leap asserts that their solution achieves a better resolution.

The headset at the moment is available only in some areas of the United States, thus it is difficult to get one (but possible, using forwarding companies), and has a price of 2300$.

This device is divided in three main components: the viewer called "*Lightwear*", a portable computer called "*Lightpack*" containing most of the hardware, and finally a *manual controller*.

The Lightwear uses a combination of cameras for the tracking tasks and lenses to project the digital elements on the real world.

The core of the Lightpack is instead a Nvidia Tegra X2 chip coupled with 8GB RAM and 128GB storage memory along with a 3 hours battery.

The advantages and disadvantages of this headset solution are described in Table 2.1.

MAGIC LEAP ONE	
ADVANTAGES	**DISADVANTAGES**
The *Lightpack* potentially allows to have a bit less weight on the head and better computational capabilities, because this portable computer can have less miniaturized components that typically are less powerful.	The *Lightpack* could reduce the usability with some NDD users, in fact some of them could have some motor and physical impairments that prevent keeping or wearing on body an additional object.
	The Devkit still is a lot sketchy and immature, it doesn't have the same level of functionality as the competition.
The field of view (the portion of the display where the user can see the mixed world, measured in angles) is slightly better than the Hololens v1 (about ten degrees more). It is instead worse if compared to Hololens v2.	The graphics quality, despite the separated portable Lightpack, it's comparable with the graphics of his main competitor (Hololens v1) released 2 years earlier.
	The device suffers from some transparency problems, preventing to give a proper experience to some NDD users.
It has been conceived as a consumer product, even if for now the Magic Leap CEO said the product it's addresses to developers and artists.	It's difficult to get one because it is mainly sold in the US and forwarding companies would be needed.
	The Magic Leap app store lacks use cases apps.

Table 2.1: Magic Leap One

Considering all this pros and cons, a different solution has been chosen for the experimentation purposes with NDD people.

2.4.2 Microsoft Hololens

Figure 2.7: Microsoft Hololens 1

The *HoloLens* [50] is a head-mounted-display (HMD) composed by a pair of mixed reality smartglasses developed and manufactured by Microsoft. It can be said that its lineage derived from Kinect, a line of motion sensing input devices for the Xbox.

It is one of the most sold HMDs of this type, even if it has still a high cost (ranges from 3500$ to 5000$, depending on the edition).

This HMD is connected to an adjustable, cushioned, inner headband, and on the front of the unit there are many of the sensors and related hardware, including a 720p display, an inertial measurement unit (IMU) (composed by accelerometer, gyroscope and magnetometer), four environment understanding sensors, an energy-efficient depth camera with a 120°*120° angle of view, a video camera, a four-microphone array and an ambient light sensor. There is even a dedicated custom-made Microsoft Holographic Processing Unit (HPU), a coprocessor in charge to process and integrate data from the sensors, as well as handling tasks like spatial mapping, gesture recognition and speech recognition. 2GB of RAM (1gb for HPU) and 64GB for data storage complete the solution. The field of view is 30 degrees horizontal, 17.5 degrees vertical, and 34 degrees of diagonal.

The pros and cons of this headset are described in the Table 2.2.

<table>
<tr><th colspan="2">HOLOLENS 1</th></tr>
<tr><th>ADVANTAGES</th><th>DISADVANTAGES</th></tr>
<tr><td>Hololens has a good usability, because it is a compact fully self-contained holographic computer integrating all the hardware in one place. This can be useful for some NDD people needing to bring the fewest number of additional objects with them during the experience. Moreover, it is comfortable wearing and allows to keep glasses (unlike other XR competitors), a very important point for some NDD people having medical eyeglasses prescription.</td><td rowspan="2">The field of view (FOV) is a bit narrow in the Hololens 1. This makes emerge some limitations in the “immersivity” of the applications. However, this FOV abundantly covers the area related to the macular human vision (including a portion of near peripheral vision) that is the most important area of human sight, where the focus is concentrated, therefore the experience is not compromised and for some NDD people it can even be an advantage because in this way they keep a strong contact with the real world [80].</td></tr>
<tr><td>The devkit is continuously in development and it is already full of many capabilities. It is open-source and it is 2 years ahead with respect to competitors. Integration with the Unity framework is supported and recommended, allowing easier development.</td></tr>
<tr><td>Support forums are full of experienced developers with previous experience.</td><td rowspan="3">Hololens at the moment has got a higher price than competition, despite the fact that Microsoft offers rental solutions. For this reason it is a product mainly conceived for enterprise usage.</td></tr>
<tr><td>The app store has already some good use cases.</td></tr>
<tr><td>The device is directly sold also in Europe.</td></tr>
</table>

Table 2.2: Hololens 1 pros and cons

Considering all the advantages and disadvantages discussed above, it has been decided to choose **Microsoft Hololens** for the experimentation of the innovative *TMR* interaction paradigm with smart objects for the NDD field.

Moreover, an upcoming release of a new Hololens version is coming, increasing the probability that this platform will be supported for a long time.

HOLOLENS 2

Figure 2.8: Microsoft Hololens 2

On the 24th of February (2019) at the Mobile World Congress (MWC) of Barcelona it has been presented the Hololens 2. The launch price is 3500$. In this upcoming release (planned for the second trimester of 2019, at the moment only in the US) there are huge improvements:

- The field of view (FOV) is substantially wider: 52 degrees of diagonal, with horizontal FOV of 43 degrees and vertical FOV of 29 degrees). The FOV *area* has been more than doubled (2.4x) with respect to the first version. This could be very useful to increment the involvement and efficacy of the applications, also the ones dedicated to the NDD field.
- Hardware and computational capabilities are greatly improved: 2k display, real-time eye-tracking, improved hand tracking (two-handed fully articulated model), a lot of new gestures for a more natural and direct manipulation, iris-based biometric identification and the newly integrated Azure Kinect sensor for depth sensing.
- Completely redesigned structure for an even more comfortable experience. The weight of the headset has been decreased and redistributed with design choices to improve the usability.
- Support introduced for both Unity and Unreal frameworks.

As it can be inferred, this new upcoming headset could greatly enhance even more the effectiveness of the applications dedicated to NDD people.

In Table 2.3 it is presented a summary comparison between the aforementioned MR devices.

COMPARISON BETWEEN CURRENT MR DEVICES			
Aspect	**HOLOLENS 1**	**HOLOLENS 2**	**MAGIC LEAP ONE**
Usability	Self-contained holographic computer, all hardware in one device. Eyeglasses can be worn.	All hardware in one device, with improved comfort and weight. Practical flip-up visor.	Less weight but three main components, for some NDD users could be a disadvantage.
Capabilities	Toolkit constantly in development and two years ahead with respect to competitors.	The Hololens toolkit is evolving to support the new capabilities of Hololens 2. Graphics increased.	Sketchy toolkit. Graphics comparable to Hololens 1.
Use cases apps	Limited number of use cases apps but well designed for various fields.	Few use cases specifically targeting the new headset.	Very few use cases.
Frameworks	Unity.	Unity, Unreal.	Unity, Unreal.
Support	Many support forums with some experienced Hololens developers.	The same legacy forums for Hololens.	Few experienced Magic Leap developers in forums.
Availability	Worldwide	Soon in US and few other countries (not Italy for now).	Only US (needed forwarding companies for Italy)
Price	From 3500 $ to 5000 $	3500 $	2300 $
Common aspects MR devices	They keep the contact with the real world, mapping the environment and mixing it with virtual elements. They also leverage spatialized sound techniques to enhance the reality of the experiences. Graphics quality increased only in Hololens2.		
Common limitations MR devices	Black or reflective surfaces are mapped imprecisely, as well as strange room shapes. Illumination gives problems if excessive (causing virtual elements to become invisible) but can be solved with additional supports if those devices are used outdoors. The battery lasts some hours, but for most type of usages in the NDD field could be more than sufficient.		

Table 2.3: MR devices comparison

3 Needs, Goals, Requirements

In order to understand the needs of the field that was being approached, initially there have been read some scientific papers about Neurodevelopmental Disorders and the results achieved with the existing traditional therapies.

Then the research continued with studies regarding the application of new technologies like VR, AR and MR to the NDD field, in order to better understand the mechanism behind the effectiveness of those new approaches, with a particular focus on the Mixed Reality.

At that point the supervisors of this thesis have been met to define some preliminary needs, goals and requirements of the application. Some technological solutions were available to choose, each one having particular characteristics and purposes.

With all this information in mind, some brainstorming has been done to define the various aspects of the proposal and the best technology that would have produced the best results considering the NDD context.

This preliminary proposal has been shown to the thesis supervisors and it has been chosen the technology to work with. From the discussions that emerged in those meetings, new ideas and suggestions have arisen about the features that the application should have had and in which way it could have improved the conditions of people with NDD.

Trying to focus on the main concepts and requests, it has been decided to create a new therapeutic tool in order to experiment the combination of smart objects along with mixed reality, and to provide an additional and different system to people with NDD, given that the MR field is still unexplored and lacks solutions, especially for them.

The process of finding the requirements has been iterative, and each of them has been thought together with therapists and psychologists with many years of experience in the NDD field.

The system needed to be as customizable as possible, in order to take into account the different needs of each user, because the more a tool can be adapted to different requirements and objectives, the more it can be effective.

3.1 Main target groups and profiling

The system has been conceived with the objective to be easily used by different kinds of users, with a special attention for people with NDD (especially children) and caregivers. Moreover, it has been designed not only for people with NDD, but also for people without impairments wanting a more challenging experience from this application.

This implies a certain number of stakeholders involved in this work.

People affected by NDD

The main target group of this system is represented by people with NDD, that could benefit from its usage. The experience can be customized by the therapist thus can be adapted for different type of impairments and users. In fact, each user could have either more cognitive-related impairments or motor related ones, and unfortunately they can also coexist. It must also be considered that they are not practical about technology, therefore they need a high degree of usability and accessibility while using applications. This type of users will be called also “Patients” or “User-patients”.

Therapists, educators and caregivers

Therapists (doctors, psychologists and psychiatrists) or educators are the second target group of this work, people who directly take care of subjects with NDD in centers or specialized schools and so that will use this technology for therapeutic purposes. They could be also families and patients’ caregivers. In fact, the equipment to set up the same experience at home could be lent in some situations, or rent. This would allow to continue the learning process in a well-known environment, which can be very helpful.

People without impairments and developers

An additional third target group that has been considered includes people without any impairments (from kids to young people) looking for an involving and challenging experience. In fact, the system has been conceived to be also a complete game application, flexible enough to provide a complex experience to the most advanced users, even if they are not the core of this research. It is also an experiment to test the potential capabilities of the Hololens and the interaction between Hololens and Smart Objects (plus image tracking), to explore the potential and limitations of the technology involved. Therefore people working in the computer science field, or designers, can also be included in this target group.

In Table 3.1 it is presented a more specific profiling of the main target users with some reasonings about possible preliminary goals of the application for each one of them.

Main target groups			
#	**Users**	**Profile**	**Goals**
1	People affected by NDD	People with a motor or cognitive impairment of various typology. They are not generally expert about technology and could be both amazed or annoyed by this type of situations, but they could have already participated to some previous experimentations.	*Attempt to improve their skills and their condition. *Attract users to this type of experimentation.
2	Therapists	People expert about cognitive impairments and psychology. Quite experienced about technology. They could be interested in using new type of applications if they improve patients conditions.	*Attempt to give therapists a tool they could use to do different activities with their patients.

Table 3.1: Main target groups and profiling in detail

In Table 3.2 instead is reported some general information about of the secondary target groups considered.

Secondary target groups			
#	**Users**	**Profile**	**Goals**
1	Kids and young people	Children between 5 and 13 or young people between 14 and 18 years old with a limited budget. They are looking for fun activities and games. New generations are generally experienced with technology and games, so they can be more critic about applications.	*Give them an innovative and engaging experience.
3	Adults working in the CS field, developers, designers	People starting from 18 years old working in the XR field and content producers. They could be interested in the potential of this new technology. They have more budget.	*Show them the potential of the innovative TMR interaction paradigm.

Table 3.2: Extra target groups, general information

3.2 Needs addressed and context

Firstly the research studies and secondly the discussions with therapists have confirmed that one of the approaches commonly used to help patients with NDD is the gamification applied to the learning of some practical skills. This methodology allows therapists to make them execute some needed exercises in a more comfortable and effective way. Through these treatments the patients can improve their motor skills, the attention span, social capabilities and enhance generalization abilities.

Even so, it is not easy to keep these patients engaged while making these exercises, since people with NDD tend to get easily distracted by unimportant details and find it difficult to properly understand the mechanisms and rules of those activities.

That's why simple and interactive games capable to focus their attention could increase the benefits of the traditional approaches. In order to make this type of training really effective therapists should be able to have complete control over the task.

In particular, this research has focused on the following main needs:

- People affected by NDD need a simple and understandable experiences, that keep them concentrated and engaged on the motor and cognitive tasks they have to do. They need also to maintain some contact with the reality in order to avoid isolation.
- Therapists need the possibility to customize as much as possible the experience for people with NDD, adapting it depending on the necessities of each one of them. They need different tasks addressed to the various type of motor and cognitive impairments and a way to eventually combine them into the same experience.
- Therapists should be able to monitor what patients are watching while they are involved in the mixed reality environment and feedbacks to control if the tasks are being correctly executed.
- Finally, therapists need a way to collect useful data during a session of use and should be able to visualize it later, so they can analyse the behaviour of each patient evaluating the improvement of a particular skill and draw conclusions from it.

Moreover, an additional need could be the exigency to explore the potential of this new type of technology consisting in the combination of the MR with smart objects, in order to evaluate its effectiveness, especially in the NDD field, since no studies have been done about this experimental approach.

3.3 Goals

The main goals of the project have been to provide an interactive and customizable system for therapists capable to improve some motor and cognitive skills in people with NDD, therefore attempting to improve their quality of life. This system has the shape of a game in order to leverage all the advantages related to the gamification of therapies that have been previously discussed, and to make user-patients feel much more comfortable in doing the exercises. In fact, an important objective of this project has been to make the experience enjoyable enough so that they don't feel like they are doing a therapy, otherwise some of them could react with indifference or even anger.

The idea has been to give therapists a customizable mixed reality game divided in some different experiences containing various possible tasks leveraging the usage of the Smart Dolphin as both a gameplay element and a feedback instrument for the caregiver.

To give a more precise idea of the objectives of the system, the main goals related to people with NDD have been divided in some sub-goals here exemplified along with some of the ideas to accomplish them:

- **Motion abilities improvement:** making the user move in a certain correct way or avoiding some obstacles.
- **Concentration skills enhancement:** requiring the user to keep track of a process (like the need for the dolphin to keep a good level of energy eating some food, for example); using some stratagem and effects to capture user's attention.
- **Orienteering capabilities improvement using hearing:** all the elements in the game could emit a spatialized sound useful to complete certain tasks.
- **Memory and reasoning reinforcement:** requiring the player to remember something to complete a task; suggesting to the player so use reasoning to find some objects in the room.
- **Learning capabilities enhancement:** putting some teaching elements/fun facts in the game and structuring it so that the users could learn something in a more relaxed and interactive way. Then the caregiver could verify the learning talking with the patient about those facts.
- **Social skills improvement:** during the game the therapist and the player typically are involved in a talk about what the player is seeing and what task he/she has to do. Other users with impairments could be involved in the talk, because the gaming experience can be streamed in a monitor.

From those sub-goals there have been extracted some tasks that the user should accomplish. Depending on the impairments and their severity, more or less tasks can be added to the game, therefore increasing or decreasing the difficulty.

Apart of the main objectives (summarized in Table 3.3) it has been added an additional goal that could affect in a positive way the development of the XR field and its consequent application also for the intellectual and motor disabilities.

Attract people/users/therapists to this technology: *Mixed Reality* and *Tangible Mixed Reality* are experimental technologies. At the moment they are mostly used by enterprises. This project could contribute in showing the potential of this technology to therapists and developers, attracting more people on the XR field. As a consequence, more interest about projects for NDD people involving *Tangible Mixed Reality* could arise.

Rank	**Goal**	**Who is involved**	**Impact**
Main goal	Attempt to Increase motor and cognitive capabilities in subjects with NDD	-User patients -Therapists -Therapeutic Centers	*Patients could show an improvement in some skills *Patients could become more involved and interested in doing future experiments.
Main goal	Give therapists a customizable system as a complement to traditional therapies	-Therapists -Therapeutic Centers	*Therapists could have an additional instrument, offering experiences not replicable in the real world, to improve the efficacy of their therapies.
Add. goal	Attract more people, users, therapists to Tangible Mixed Reality technology	-New therapists -Reviewers -Early adopters users	*There could be an increase in requested projects leveraging this type of technology. *Therapists could support the diffusion of technologies in educational therapeutic contexts.

Table 3.3: Goals in detail

3.4 Requirements

Taking into account the analysis about the target users, needs and goals, there have been extracted a set of requirements for the system satisfying the mentioned needs in order to achieve the objectives discussed. Starting from these requirements, then, a design solution for the application has been built.

The main requirements of the system are:

1. **Gameplay including motor and cognitive tasks**
   The application should have a motor task (collection of flowing objects with a correct rotation, obstacles avoidance), a concentration task (periodical action and monitoring), sound orienteering task, memory task and some learning tips.
2. **Customization of the experience**
   The therapist must be able to personalize the interactive experience by adding/removing tasks and changing parameters to adjust the difficulty of the game depending on the impairments of the user.
3. **Interaction between the Mixed Reality headset and the Smart Object**
   The system has to allow interaction between the Hololens and the Smart Object. Mutual communication is preferred. The interaction should enhance the experience and could help in completing some tasks. Problems occurring at the communication between the Hololens and the Smart Object should not interrupt the application or the training.
4. **Data Collection**
   The application should be able to collect data regarding each training session. In this way the therapists could analyse the data and keep track of the possible improvements of each user skills.
5. **Monitoring and feedbacks**
   The therapist should be able to observe in detail the training session. What the user patient is currently watching should be streamed in a display if necessary. Feedbacks coming from the headset and the Smart Object should keep giving hints to the therapist about the execution performance of the user.

Other additional requirements taken into consideration are:

6. **UI simple and involving**
   The system should have simple and involving interaction mechanisms and an intuitive UI tailored for people with NDD and therapists.
7. **Content compelling**
   To involve users the app should have compelling graphics and content.

In the Table 3.4 are presented in detail all the requirements and sub-requirements. Most of these take into account the impairments previously discussed, trying to define a more concrete structure for the application and the tasks needed by NDD users to improve motor and cognitive skills. At the same time other requirements regard the objective to make the experience as compelling as possible, in order to fully leverage the gamification approach thus improving the efficacy of the solution.

#	Dimension	Requirement description	Motivation
R1.1	App architecture	Required a motor task: the user should move and rotate in a certain way to collect some flowing elements. Additional sub-task (activatable on need): the user should avoid obstacles	Attempt to improve motor skills for user patients with motor impairments
R1.2	App architecture	Required concentration task: the game structure has to involve the player concentrating into a particular task and use effects to capture his/her attention over some elements	Attempt to improve focus and concentration skills for user patients with the related impairments
R1.3	App architecture	In the mechanism of some tasks, sound should have an important role in helping the player/patient to complete them, improving his/her orienteering capabilities.	Attempt to improve spatial perception skills using hearing for patients with those impairments
R1.4	App architecture	Required a memory/reasoning task: the user should reason and remember something in order to complete certain tasks	Attempt to improve memory and reasoning capabilities of patients with the respective impairments
R1.5	Content/ Message	The game should leave a “Message” or a teaching	Attempt to give teachings in an interactive way
R1.6	App architecture	The game must have a tutorial explaining the basics and how to play	Need to explain the basics of the application for some users
R2.1	App architecture	The therapist should be able to customize the experience by adding/removing tasks and adjusting the relative parameters. Due to the fact not all patients have the same motor impairment, it is necessary to accept a certain degree of error of this movement. This degree of error should be customizable depending on the user	Need to give to the therapists a customizable system to suit the different needs of NDD people.

R2.2	App architecture	The game has to be structured in multiple layers. Additional tasks should be added or removed to increase the difficulty, depending on the patient conditions	Need to structure the game depending on the impairments the patient has got
R2.3	App architecture	The application should have more than one play mode in order to enrich gameplay and give users more experiences	Need to satisfy necessities of various target users
R3	Interaction and Communication	Required Interaction between the Mixed Reality headset and the Smart Object. Mutual communication preferred. Communication problems shouldn't interrupt the training	Need to enhance the effectiveness of the solution introducing a Smart Object capable of reacting to some actions
R4	DB architecture	The app must have a way to save statistics about the match, in this way it can be compared over time the improvement of the user patients.	Need to extrapolate statistics of the played matches, to evaluate increment of skills
R5	Monitoring	Required possibility for the therapist to monitor the training through the streaming of the content seen by the patient and feedbacks coming from the Smart Toy.	Therapist needs monitoring and feedbacks
R6.1	UI	The app needs a simple interaction mechanism and an intuitive UI. Difficult interactions should be reduced to the minimum, previous researches [4] highlighted that some Hololens gestures are unintuitive for patients with NDD	Need a simple but effective interaction with UI and game elements
R6.2	UI	The app should be involving without overwhelming too much the player with content, especially during the tasks.	Need to make a simple and effective app in terms of content
R7.1	Content	The app should have quite compelling content, effects and graphics to attract users interest	Need to attract children and patients attention
R7.2	Content	The game has to be realistic and involving to let the patients enjoy the experience, but the graphics should be distinguishable from real world because some patients with impairments may get confused. Should be considered a cartoonish graphics style.	Need a quite realistic look and feel without confusing patients about what is real and what is virtual.

Table 3.4: Requirements in detail

3.5 Constraints

Based on the requirements highlighted above, it came out that the system going to be defined has some limitations due to the client-server architecture involved. If the therapeutic center wanting to use the system doesn't have a LAN connection, then the Hololens and the Smart Object can't interact.

Other constraints are more relative to the experimental technology involved. In fact, some observations pointed out that Hololens Spatial Mapping module (in charge of mapping the environment, as Figure 3.1 depicts) have some problems in detecting black surfaces, mirrors or strange room shapes, that could reflect in a wrong or imprecise mapping. Technological improvements will be capable to remove this constraint.

Also the room dimensions can give some limitations. In fact, if the room is too small (approximately less than 2.5 squared meters) the experiences are compromised. If instead the room is too big (approximately more than six squared meters) the experiences are not compromised but only some portion of the room will be mapped and transformed.

Figure 3.1: Hololens mapping the environment

ASSUMPTIONS

Since some of the constraints are related to hardware and software properties of Hololens, some assumptions need to be made:

The main assumption that has been considered to obtain a good experience is that the room where the application runs should be rectangular, as empty as possible and with a dimension mandatorily bigger than 2.5 squared meters and possibly not exceeding six squared meters.

Black coloured elements and mirrors should also not be present in the room to obtain a good mapping. All these facts have been kept into consideration in order to make design choices.

Finally, for those therapeutic centers wanting to use the system, a dedicated router already configured should be given, or it should be assumed they have at least a LAN Wi-Fi connection.

Nevertheless, during the development some solutions have been leveraged in order to remove most of those assumptions, letting the application run almost anywhere.

4 Design

This chapter describes the design of the application applying the TMR paradigm based on the requirements previously defined. The design has been subject to a trade-off between technology potential and ease of use constraints. Most HoloLens and Smart Toy capabilities have been leveraged, but at the same time there have been avoid features that could have reduced the comfort and usability.

For these reasons, also in this case an iterative approach has been adopted. After designing the structure of the application and developing it, the testing phase was crucial in order to understand which changes were needed in the design in order to obtain a user-friendliness application. Due to the experimental technology involved, those iterations happened multiple times and much more than required by other applications developed.

4.1 Along the Oceanic Flow

4.1.1 General Design

Along the Oceanic Flow (ATOF) is an application for HoloLens that surrounds the end-user with world-anchored virtual elements while still maintaining contact with the reality. The user, leveraging a Smart Object represented by a dolphin, has to complete some experiences by doing motor and cognitive tasks like collecting elements, avoiding obstacles and finding a way to open treasure chests in his/her own room transformed into an ocean floor full of interactive decorations.

The main purpose of the system is to help therapists and educators in their work with people affected by NDD providing them an application aiming to improve user patients' motor and cognitive capabilities. The therapists can observe what the user patient is doing by streaming the content of the device directly on a computer, as well as leveraging feedbacks given by the Smart Object.

ATOF considers mainly two types of users:

- **Supervisor** (therapist, evaluator, caregiver or developer), who previously customizes the experience and then monitors the end-user at runtime.
- **End-user,** who experiences the blended *TMR* environment wearing the HMD.

The application firstly scans and transforms the room where the device is situated (adding decorations, sand, water, interactive elements), and once finished it provides three possible experiences that can be enjoyed, each one with a different effort required.

The therapist can simply make the user patient **explore the transformed room** and let him/her interact with decorations, changing them whenever wanted with some involving effects (Figure 4.1). Otherwise he/she can make the user patient play two game modes: *Infinity*, *Adventure*.

The **Infinity mode** is an experience fully customizable by the therapist: the user has to take the Smart Dolphin and go inside an aura that appears in the room attracting him/her. When this aura is entered a countdown starts. Once the countdown is finished, a generator is activated in front of the player area and some elements are spawned and travel towards the player. The player has to use the Smart Dolphin to take the bubble rings and avoid obstacles (if activated) that decrease player's health in case of collision. Obstacles, duration of the game, additional tasks, and lot of other parameters can be customized. It is called infinity mode because the duration of the game can be made potentially infinite. In this case the game ends when the dolphin loses all his health.

The **Adventure mode** is the most complete experience and includes two games. It is based on a story (reported in the following paragraph) and it has got 3 levels of increasing difficulty. Each level is divided in two parts. The first part of each level is the same as the *Infinity Mode*, that is, the user has to travel the oceans catching bubble rings with the Smart Dolphin and avoiding obstacles. The second part of each level is a *Treasure Hunt* game: the dolphin gets stuck on an ocean floor and must find a way to continue his adventure. He has to explore the room finding a key emitting a spatialized sound (or a password, in the last level). This key opens a treasure chest where a map is contained. Once the map of that part of the ocean is caught, the dolphin knows how to continue the adventure and the next level begins.

Data about both the *Infinity mode* and the *Adventure mode* is saved in the folder of the application, allowing therapists measure improvements of NDD users over time. The saved data can be seen also inside the application, both in a chronological way (with all the details) or ordered by best match in a billboard with the three best users and their relative score.

Two *tutorials* with a different difficulty are included to let users get some practice before starting a real match. Those tutorials are especially useful for people with impairments because they are very simple and designed specifically for them, following the feedback of the educators. Furtherly, they represent additional exercises to improve their skills.

The story of *ALONG THE OCEANIC FLOW*

There is a young dolphin named *"Phil the Dolphin"* that wants to make an adventure to become an adult. He wants to travel along the oceans far away, but he's not experienced. The player has to help Phil make this adventure, following a path composed by bubble rings that are traces left by more experienced dolphin travellers.

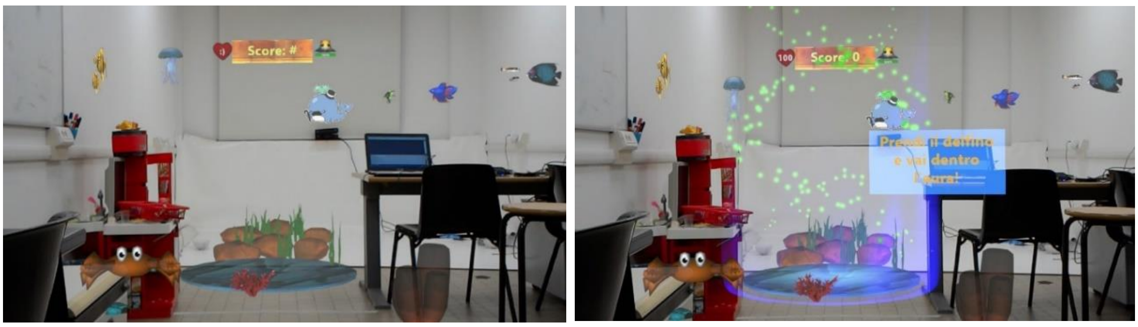


Figure 4.1: decorated interactive room (on the left) - starting an experience (on the right)

4.1.2 Infinity Mode and customization details

In the Infinity Mode, as already said, the aim is mainly to use the Smart Dolphin to catch the bubble rings. However, it is a completely customizable experience, therefore the objectives of the experience and the difficulty can be changed. The parameters that can be adjusted by the therapist are manifold. In Table 4.1 are reported all the customizable parameters, and in Figure 4.2 it is shown the menu where the therapist can customize the experience.

Infinity Mode Settings	
Parameter	**Description**
Active generators	Determines how many generators are active, from which the flowing elements will be generated. Increasing it's value is a way to increase the difficulty of the training. Value ranging from 1 to 4.
Initial health	The initial health of the dolphin. Can decrease due to collisions with obstacles, for example, or with rings taken incorrectly.
Number of waves	Desired number of waves (composed by elements) to be spawn.
Elements per wave	Desired number of elements per each wave.
Spawn wait	Rest time between elements.
Wave wait	Rest time between waves. This is the spare time where some teaching bits could be visualized.
Speed elements	The desired speed of all the flowing elements.
Error tolerance rings	The maximum admitted error between the rotation of the Smart Dolphin and the rotation of the ring. Lowering this value increases the difficulty. It's an indicator of the precision required.
Max rotation left	Maximum rotation to the left admitted for a ring.
Max rotation right	Maximum rotation to the right admitted for a ring. During the game a random rotation of each ring will be selected between the max rotation left and the max rotation right.
Obstacles (On/Off)	Activates an additional motor task where the player has to avoid some objects (a can and a broken bottle).
Sharks (On/Off)	Activates another additional motor task more difficult (sharks will follow the player).
Energy (On/Off)	Activates the energy refilling concentration task, where the player has to eat some food (little cartoonish octopuses) to keep a good level of energy.
Cultural Bits (On/Off)	Activates the teaching messages appearing between waves.

Powerups (On/Off)	Activates the possibility that some powerups are spawn. One powerup is a heart increasing the health of the player, the other one is a sphere called "X2" that doubles temporarily the speed of the flowing elements and the points taken.
Energy consuming time	Time interval before the energy bar is decremented by one unit. Valid only if the energy toggle is activated.
Spawn wait powerups	Wait time before a powerup is spawned. Valid only with powerups active.
Timer X2 powerup	Duration of the X2 powerup (the one that temporarily speeds up the velocity of the elements and doubles the caught points). Valid only with powerups active.

Table 4.1: Infinity Mode settings

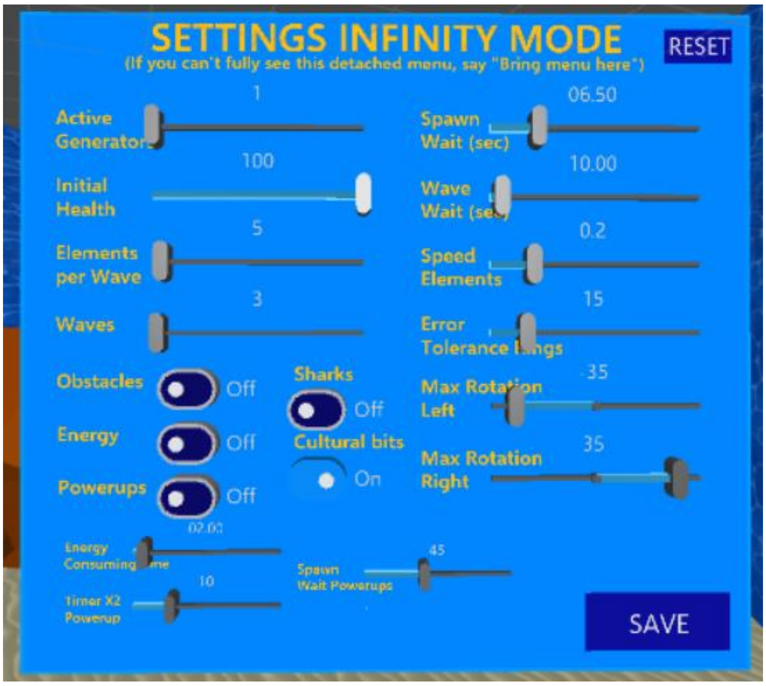


Figure 4.2: Infinity Mode settings panel

As it can be noticed, the tasks included in this experience are mainly three, and they can be added or removed on top of the basic task ("rings catching") depending on the therapists needs for the user:

- **Motor tasks:** "*Obstacles*" and "*Sharks*". Apart of catching bubbles the user has to avoids also hazards.
- **Concentration task:** "*Energy*". The user has to keep refilling the energy of the dolphin eating some food.
- **Learning task:** "*Cultural bits*". The user can learn something about the creatures of the oceans in the spare time between waves.

Smart Dolphin interaction

During these experiences the interaction with the smart object is continuous. Green leds are turned on for a second when the user correctly takes a ring. Instead, red leds are turned on for one second when the user takes a ring wrongly. Moreover, if the user presses the dorsal fin or head of the Smart Dolphin then funny sounds and effects are played on the Hololens consequently. These two actions also increase dolphin's energy when the concentration task (energy refilling) is active.

Gameplay and rules

Once the user goes with the Smart Dolphin inside the aura to start the experience, the rules and the gameplay are these:

- The user can leave the aura for a maximum of ten seconds to avoid obstacles, otherwise the dolphin's health starts decreasing until he/she returns inside it.
- If the user takes correctly a ring the score increases; If the player takes wrongly a ring the health decreases.
- If a ring is missed and goes out of the playfield boundaries, the health of the dolphin decreases.
- If the user takes an obstacle, score decreases. If the user is bitten by a shark, health and score decrease.
- Food (little octopuses) increases the energy and the score.
- The powerup with the heart shape increases the health. The X2 powerup temporarily increments the speed of the flowing elements, and the points caught or lost during that time interval are doubled.
- The objective is to finish the experience. In case the Infinity mode is made really infinite, the objective is to obtain the best high score on the billboard.

In Figure 4.3 it can be seen a preview of the Infinity Mode with rings, obstacles and food.

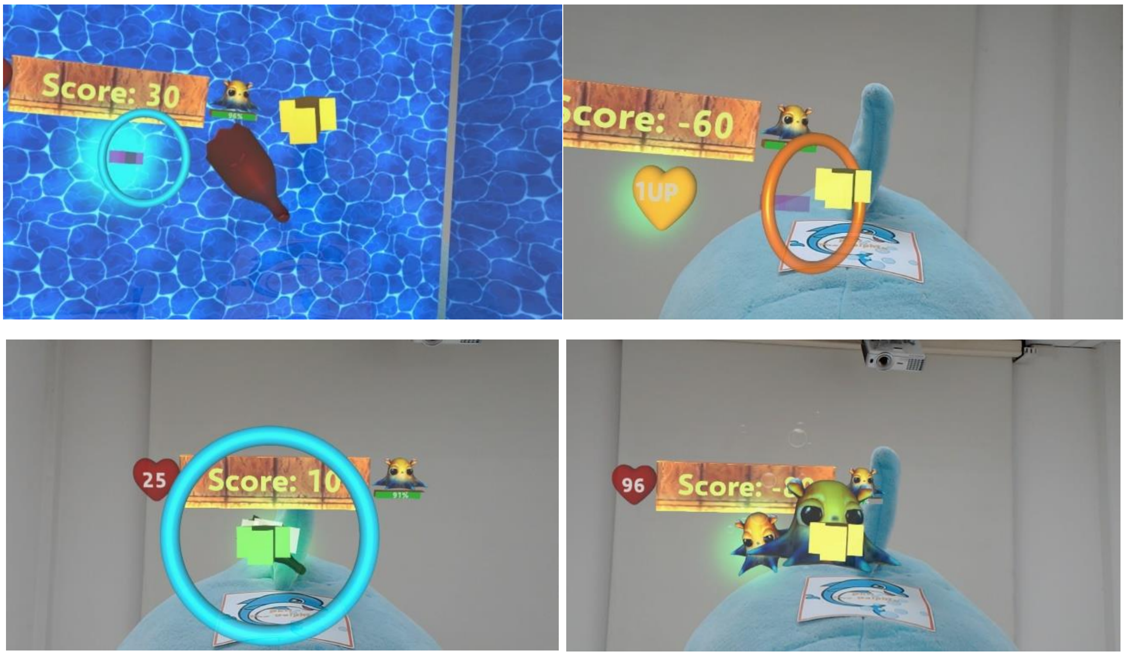


Figure 4.3: Infinity Mode. When the user doesn't avoid obstacles (up-left) or takes incorrectly the bubble rings (up-right), as a visual feedback they become red, and the score is decremented. – When the user takes correctly a bubble ring, the arrow becomes green (down-left). Octopuses are the food that the dolphin eats to refill the energy (down-right).

4.1.3 Adventure Mode details

The Adventure Mode, that is the most complete experience, is structured in three levels of increasing difficulty, and each level is divided in two parts. The first part is like the Infinity Mode, therefore with flowing elements to catch or avoid. The second part is a treasure hunt game.

The reason behind is the fact that the inexperienced young dolphin, with the help of the user, wants to travel the oceans far away, but at some point he gets stuck in an ocean floor and needs to find a way to continue the adventure (this is the point where the treasure hunt phase starts). Once the user gets the map of that portion of the ocean (that is contained in a treasure chest), the dolphin can continue his adventure and the next level begins.

The detailed structure of the *Adventure Mode* is reported in Table 4.2.

Adventure Mode structure of levels		
Level	**Phase**	**Description**
Level 1	Travel-Flow	1 generator active, Energy task active, Obstacles active, Powerups active, Cultural Bits active.
	Treasure Hunt	1 key (emitting a spatialized sound) to find around the room in order to open the treasure chest containing the map (sound orienteering task and reasoning task).
Level 2	Travel-Flow	2 generators active, Energy task active, Obstacles active, Sharks active, Powerups active, Cultural Bits active. Changes in parameters to increase difficulty: increased elements speed, increased max elements rotations left and right, increased generators, lowered error tolerance.
	Treasure Hunt	2 keys (emitting spatialized sounds) to find around the room in order to open the treasure chest containing the map (sound orienteering task and reasoning task).
Level 3	Travel-Flow	4 generators active, Energy task active, Obstacles active, Sharks active, Powerups active, Cultural Bits active. Changes in parameters to increase difficulty: increased elements speed, increased max elements rotations left and right, increased generators, lowered error tolerance.
	Treasure Hunt	Random-generated password attached to one painting. Once found, it has to be remembered to insert it in the treasure chest numeric keypad (memory task and reasoning task).

Table 4.2: Adventure Mode, structure of levels

As it can be noticed, this experience includes all the motor and cognitive tasks that *ATOF* offers, distributed in the following way:

- **Travel-flow phase**
  includes **motor tasks** (*Obstacles*, *Sharks*), **concentration task** (*Energy*), **learning task** (*Cultural Bits*).
- **Treasure Hunt phase**
  includes, depending on the level, **sound orienteering task, reasoning task, memory task.**

The gameplay and rules of the Travel-Flow phase are the same as the ones of the Infinity mode. Regarding the Treasure Hunt phase, there is no time limit to complete it. The time of completion is saved along with all the other statistics and serve as an additional indicator for the therapist to observe if the user patient is improving over time.

These two phases of the *Adventure Mode* have been structured in a complementary way. In the Travel-flow phase the user has to move while staying in a limited area (the aura) to get the rings and avoid obstacles; in the Treasure Hunt, instead, the player has to mildly wander all around the room while reasoning with no hurry, remembering things and orienting with hearing capabilities. A preview of the Treasure Hunt phase can be seen in Figure 4.4.

Figure 4.4: Adventure Mode, Treasure Hunt phase. Chest opened after finding the key.

4.1.4 Tutorials

ATOF includes two simple tutorial exercises, of increasing difficulty, to let the user get some practice with the game mechanisms while already attempting to improve some motor capabilities. The tutorials are designed specifically for people with impairments and they prepare the user for the *Infinity Mode*, to which they resemble.

In the tutorials the rules are very simplified. Health, energy and score are not active. Only one generator is active. The objective of the tutorials is just to get some practice in taking the rings with the right rotation.

Basic Tutorial

This is the simplest tutorial and it has been made considering the feedback given by the educators during the experimentations of the *ATOF* application.

The user has to get the dolphin and go inside the aura (as usual). Apart of that, the main specific design choices that emerged from the educators' feedback have been:

- The generator can move, as it can be seen in Figure 4.5. To let users with impairments rotate with no hurry, the generator moves slowly and doesn't spawn any rings until it has reached a certain wanted position.
- Rotations just from -45 degrees to +45 degrees (with respect to player area direction) have been used to avoid excessively long rotations with waste of time and confusion.
- The generator follows a path: it starts in front of the player area. After collecting some rings it moves to the right until it is at +45 degrees. After catching some other rings it moves to the left until it is at -45 degrees. Finally it returns to the center of the player area and goes a bit down, therefore the last rings must be caught crouching.
- Rings are spawned straight, with no rotation, perpendicular to the player area.

The educator suggested the approach of making the NDD user crouch in order to leverage two physical planes, one when the user is standing and the other one when he/she is crouching.

Since the rings are generated always straight, with no rotation, the player has just to *rotate* himself, and eventually *crouch*, to collect them. The next tutorial adds the necessity to move a little laterally, in addition to rotating.

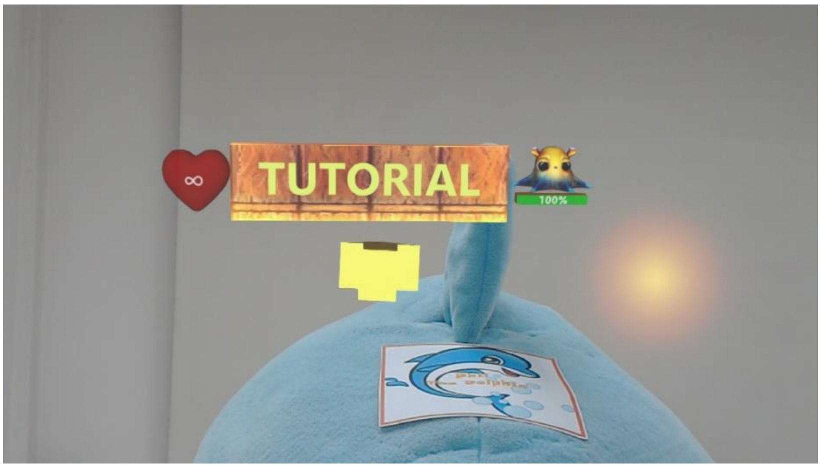


Figure 4.5: Basic tutorial. The generator is moving to the right before spawning straight rings.

Standard Tutorial

In this case it is necessary to both *rotate* and *move* a few steps to take the rings. This tutorial is already more similar to the Infinity Mode.

Rings are kept being generated straight until the user gets three of them correctly. Then rings are kept being generated right-rotated (some degrees with respect to their own axis, this time) until the user gets other three of them correctly. Finally, rings are kept being generated left-rotated until the user gets the last three of them correctly.

The functioning is practically the same of the Infinity Mode, with the exception that the rotation of the rings is fixed (and not randomized). In this way the users can practice in taking rings in specific positions. An example can be seen in Figure 4.6.

Figure 4.6: Standard Tutorial. The generator stays in its position and rings have a rotation. In this case the user needed to move a bit and slightly rotate to the right.

4.1.5 Gathering user interaction data

The system allows to collect data about the usage and the interaction, both for the *Infinity mode* and the *Adventure mode*. This is important to allow therapists measure improvements of NDD users over time.

In Table 4.3 are reported the saved values for each match.

Data saved for each match	
Value	**Description**
Number of the match	Ever increasing number representing univocally a match.
Date	Exact time date when the training has started (year, month, day, hour, minutes).
Username	Name or code of the patient.
Score	Total points that the user obtained.
Training Mode	It can be Infinity Mode or Adventure Mode.
Levels	Every match can have only 1 level (if *Infinity Mode)* or 3 levels (if *Adventure Mode)*. Values saved for each level are described in the next table.

Table 4.3: Data saved for each match

In Table 4.4 are instead reported the saved values for each level.

Data saved for each level	
Value	**Description**
Level number	Number of the level.
Rings correctly taken	Number of rings correctly taken by the user.
Total rings generated	Total number of rings generated during the level
Rate of correctly taken rings	Rings correctly taken / Total rings generated. *Accuracy* indicator of the user's performance.
Error Tolerance Rings	Admitted error between rings rotation and Smart Dolphin rotation while taking a ring. Requested *Precision*.

Avoided obstacles	Number of obstacles (can or broken bottle) avoided by the player.
Total obstacles generated	Total number of obstacles (can or broken bottle) generated during the level.
Rate of avoided obstacles	Avoided obstacles / Total obstacles generated. *Accuracy* indicator of the user's performance.
Completion time of the Treasure Hunt	Different from 0 only if Adventure Mode has been selected.

Table 4.4: Data saved for each level

In Figure 4.7 it can be seen the entire structure of the saved data.

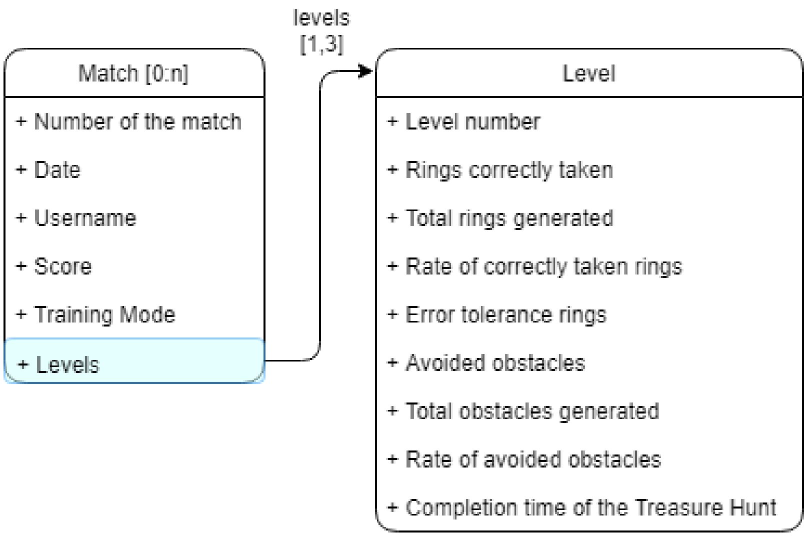


Figure 4.7: structure of the saved data

4.1.6 Activity Diagram

In Figure 4.8 it is reported an activity diagram describing the general functioning of the *ATOF* application.

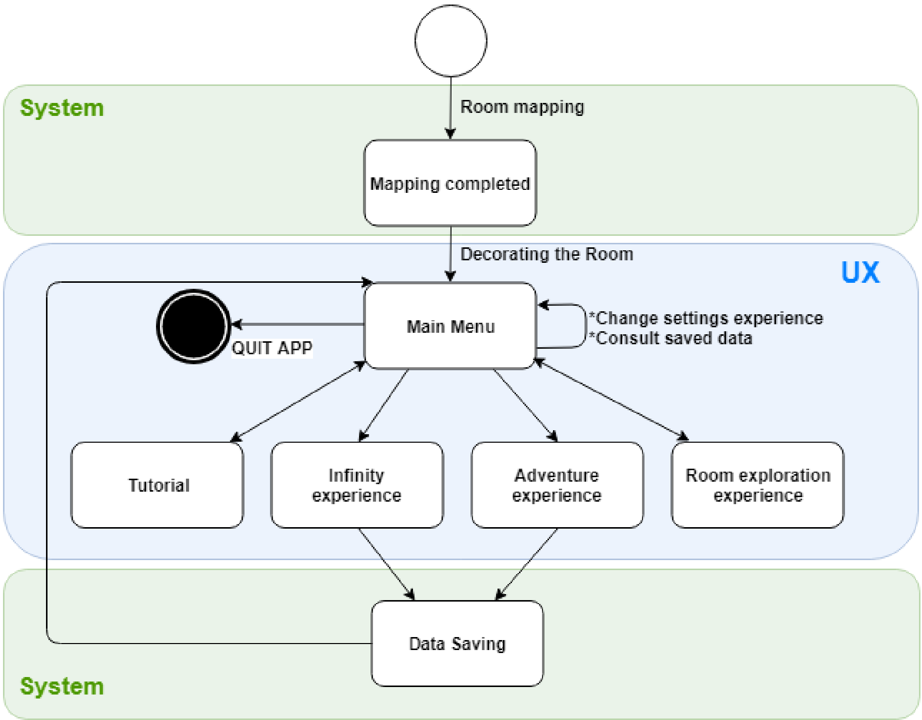


Figure 4.8: activity diagram describing the general functioning of ATOF

4.2 Design details

Designing an app for HoloLens is not simple because there are a lot of variables to consider that can influence the result and some of them are not predictable. Therefore the design of the app in this case is much more tied to the implementation constraints unlike other type of applications.

One of the first things to consider is a big difference between Mixed Reality games and more traditional apps: the space where the application can be used changes at each run.

In the HoloLens there is a module called "SpatialMapping" that is in charge of calculating the dimension and shape of the room. Depending on the size and shape of the room the customization effect can vary, either in a positive or negative way. It's impossible to foresee which type of room will be used to run the application, therefore some assumptions may be needed apart from the fact that the algorithms of the developer will try to be as robust as possible to manage most type of situations. In the following paragraphs there will be described in detail all the design choices along with their evolution during the app creation.

4.2.1 Tracking of the Smart Object

One of the most important functionalities needed by the application is the capability to track the position and the orientation of the Smart Dolphin. In fact, there is the need to leverage the tracking to allow the user to collect the flowing elements like the bubble rings.

After having done some researches it has been found that the possible choices were mainly two: track the Smart Dolphin using its internal hardware (gps, accelerometer, gyroscope), or track the Smart Dolphin using imaging recognition capabilities.

In order to obtain the greatest possible tracking precision, it has been decided to use imaging recognition capabilities. Moreover, this choice allows the tracking of the dolphin to not depend from the Wi-Fi connection, because imaging recognition is done leveraging only on headset capabilities, thus making the tracking of the position and rotation more stable.

The next choice was to decide which type of imaging recognition to perform. In fact, both 3d object recognition and 2d image recognition are available. It has been decided to use a 2d image recognition (putting a little image tag on the dolphin) because the Smart Dolphin has to be kept in the hands, and the hands cover a big portion of it preventing the recognition of the 3d object in its entirety. Moreover, some testing showed that 2d image recognition is more precise for detecting rotation.

Throughout this document terms like “image target”, “image tag” or simply “tag” will be used interchangeably to indicate the 2d image attached to the Smart Dolphin used for tracking through imaging recognition.

4.2.2 Designing the Playfield

The design of this game component has been done in two steps.

First design concept of “The Playfield”

In a traditional game there can be defined without problems the virtual boundaries where the game will be played, because they are potentially infinite. Like stated above, in Mixed Reality this is not possible, because the physical space puts a limit that an involving application wanting to use the entire room must consider. To partially overcome this problem it has been conceptualized and designed a minimum space needed to play in a comfortable way, the **Playfield.**

This Playfield defines the essential elements and space needed to play. For essential elements are meant the interactive objects used to play the game (like the flowing bubbles, in my case) and the world-anchored user interface (UI) containing the score of the player, health and energy. It has been chosen a world-anchored UI because, like stated in the chapter relative to the state of the art, in XR applications (VR/AR or MR) a good practice is to integrate the UI within the world. The other types of UIs should be avoided in XR applications whenever possible [45].

The first application concept had a vertical playfield, where all the elements of the game (bubble rings, obstacles, etc) are put at the top of a wall and “fall” down towards the floor while the player uses the Smart Dolphin to catch them. Figure 4.9 shows this first raw concept.

The reason for this design choice was mostly the fact that a vertical playfield would have occupied the minimum possible space, allowing the game to be played virtually anywhere almost in the same way. Plus, it would have allowed the game to be played even in a non-empty room and with other people doing other things, because it would have occupied just a wall. It would also have reduced the probability of hitting other things in the room while being playing and moving around. Finally, it would have allowed an easier tag recognition because the tag, attached to the rear of the dolphin and kept in hands, would have been always perpendicular to the HoloLens camera.

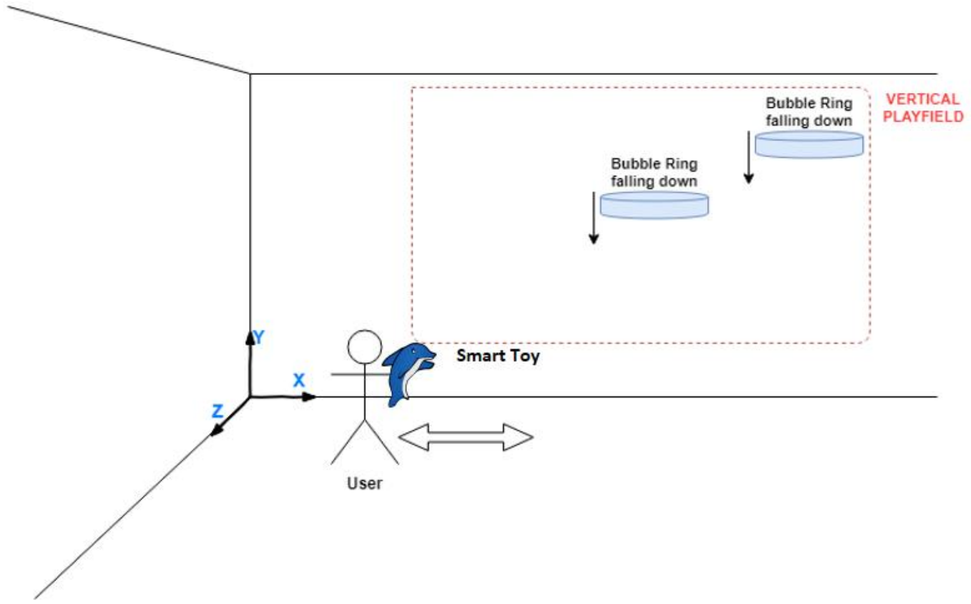


Figure 4.9: First raw concept of the Playfield (vertical)

However, at the moment of trying the HoloLens for the first time, the problems that this vertical Playfield would have entailed were immediately noticed:

- The narrow Field of View of the HoloLens would have compromised seriously the experience, because it would have been very hard to understand where the elements come from and see them precisely, especially for users with impairments. There have been suggestions about generating the “falling” elements in a corner, but at the end seemed a bad solution both aesthetically and functionally.
- The weight of the HoloLens is a bit prohibitive if the user has to maintain the head tilted up for a long time, plus the fact the device could fall in some situations.

Second design concept of the Playfield

To solve the above problem it has been necessary to change the Playfield idea maintaining at the same time the need to use the minimum amount of space to contain all the elements of the game and the world-anchored user interface.

The new idea has been to conceptualize and design a horizontal Playfield. In this case, as Figure 4.10 shows, there is the world-anchored UI directly in front of the player, a bit above player's head but always visible while playing, and the interactive elements of the game are exactly aligned with the player's head and flow towards him/her. The player still keeps in his/her hands the Smart Dolphin, but now horizontally, and tries to catch all the flowing elements coming to him/her. In this way the user can have a good view about all the elements of the game and, depending on the action made, it can be immediately seen a reaction in the world-anchored user interface in front of him/her, as expected in all traditional games and applications to have a clear idea of what's happening.

This is a good approach especially considering users with impairments, because some of them have difficulties in realize where the objects could be if they don't see them and if the position changes too much frequently, even if there is an arrow indicating the proper direction to look. This approach instead is simple enough to let all type of users play.

The horizontal Playfield solution mitigates as much as possible the problem related to the narrow field of view. Moreover, also the problem caused by the weight of the device is mitigated, because now the user doesn't have to stay with the head tilted up, on the contrary he/she has to stay straight with the back and head in order to play the game, thus quite educating users without a good posture to improve it. Still the device itself is a bit weighty for very long sessions of gaming, but at least in this way the weight is correctly distributed.

There are not only advantages in this solution. As a matter of fact, one of the cons is related to the tag recognition. In the vertical playfield concept, where the dolphin was kept in a vertical position, the tag was perpendicular to the camera, therefore its recognition was at the maximum level. In the horizontal playfield concept instead, the tag is still placed on the rear of the dolphin in order to track its movements, but it is not perpendicular to the HoloLens camera because we keep the dolphin in a horizontal position, therefore the tracking is a little bit more loosy and inaccurate. However, testing has demonstrated that this solution is however affordable and good.

Figure 4.10: second and final concept of the Playfield, horizontal (image from Unity Editor)

A necessity when using an horizontal Playfield is that users with different heights must be able to play the game. This could seem trivial, but it implies some design choices in this type of application. Like previously said, the horizontal playfield is structured so that the generator of the bubble rings is placed directly in front of the user, aligned with its head. Well, this alignment is important in order to play the game more comfortably. In fact, different persons with different heights will need different vertical positions for the generator of bubble rings.

Therefore, a design choice has been to make the generator and the world-anchored UI vertically moving, to align their position automatically with the user's head some seconds before the game starts. In this way the game can be played by children or adults without problems.

Continuing with the design of the horizontal Playfield, two other important components have been added to it:

- **Boundary of the Playfield**
- **Aura**

The necessity to design a boundary of the Playfield emerged from the fact that the flowing elements shouldn't be supposed to travel infinitely in the game, for obvious reasons. If they travelled infinitely, surely there would have been a lot of confusion in the game and a lot of performance problems when the spawned flowing objects start to increase considerably. Elements exceeding the Playfield are not interesting anymore for the user, therefore when flowing objects go out of it they should be destroyed or deactivated. This fact brought to the idea of designing an invisible *Playfield Boundary* physically enclosing the Playfield and out of which all flowing elements are destroyed or deactivated. Figure 4.11 shows it. The *Playfield Boundary* is larger than the Playfield, to allow elements go across it, go beyond it, and after a while being deactivated. This design choice allowed to keep clean the game space, but there is an additional motivation to create it. This boundary has also a gameplay role: in fact, it determines if a bubble ring hasn't been caught by the player, or if an obstacle has been avoided. This is crucial for the gameplay and for calculating the statistics of each match.

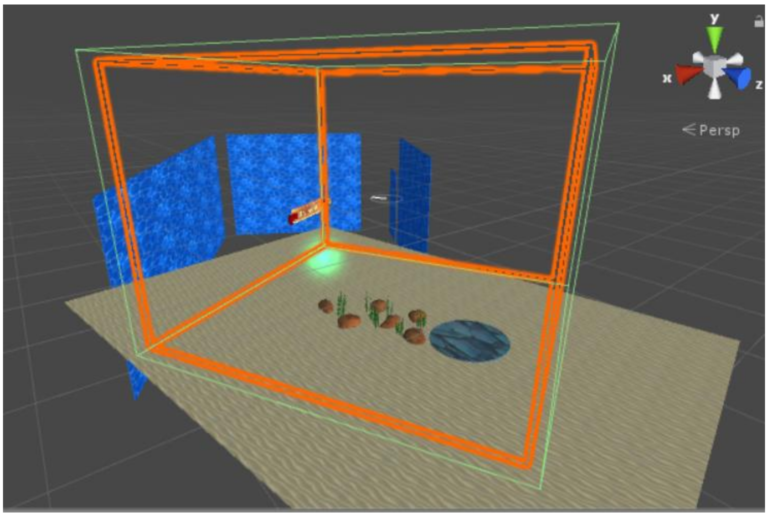


Figure 4.11: invisible boundary enclosing the Playfield, out of which all flowing elements are deactivated.

The choice to design an *"Aura"* instead came from the fact that it has been thought where the user should move to have a challenging experience. Some reasons have been considered before making a decision. As previously said, the main mechanics of this game is to catch bubble rings using the Smart Dolphin, and to do this the user has to rotate itself and move a bit. But the user has also to avoid obstacles that are coming together with bubbles.

Therefore, it has been considered the idea to add an *Aura* (shown in Figure 4.12), a player area where the user needs to stay, for multiple reasons:

- If the user is positioned inside this *Aura*, he/she can see all the elements of the game and the world-anchored UI comfortably. The elements flow towards the *Aura* where the player needs to stay.
- As said, the user must catch some elements and avoid others. To make the game more challenging it has been thought that when the player has to avoid obstacles going out from this *Aura*, he/she has only some seconds to return inside it. If the player stays out more than those seconds, something bad happens (the dolphin loses health, for example). In this way is not so trivial to avoid obstacles, this mechanism keeps the attention of the user and at the same time remembers him/her to go inside the *Aura* to have a good game experience.

This player area, represented by a platform with the *Aura* above it, attracts the player inviting him/her to go inside it when the game is starting. Once inside it the *Aura* deactivates, and the game begins.

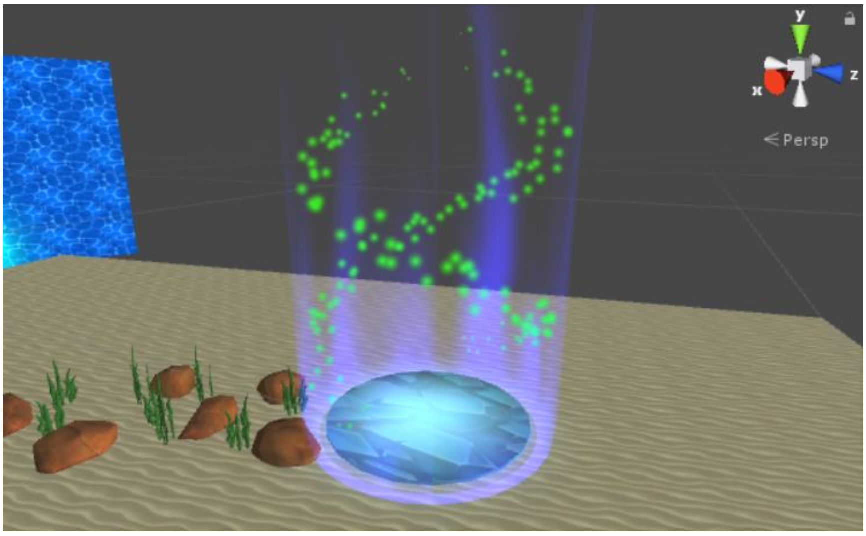


Figure 4.12: Aura

4.2.3 Interaction

HoloLens platform offers various type of interactions: *Airtap* gesture, *Bloom* gesture, Voice recognition (at the moment working only with the English language) [57][58].

The problem is that these types of interactions are difficult to learn, it is required a tutorial session just for them. This difficulty arises especially when talking about users with impairments. It would be necessary for them some additional training in order to learn gestures before even playing the game [4][5].

The "*Airtap*" gesture is often used in HoloLens applications as main mechanism of interaction. This gesture is the equivalent of the "click" in the desktop platforms, but in HoloLens consists in closing the index finger over a thumb while maintaining closed the rest of the hand. At the same time the cursor (aligned with the head, independently of fingers position) must point to the element we want to interact with.

From an interaction design point of view, this gesture is quite hard to learn for some users, and to master it takes a bit of extra-time also for users without impairments. The relative papers of the applications cited above observe and describe this problem [4][5]. Elderly users (like in MemHolo app [4]), users with impairments or users not familiar with technology can become frustrated or demoralized if they can't learn the gesture.

A mitigation could be the usage of the "*Clicker*" [4][49], a little remote-control button included with the HoloLens, that at least avoids the problem of having to learn the gesture. In this way the only problem is to synchronize the gaze with the click of the button. In the *ATOF* application the Smart Dolphin occupies both hands, so it wouldn't have been a very practical solution.

For these reasons in this application has been tried a different approach. Instead of using those gestures as the main interaction paradigm, it has been simply used the movement of the Smart Dolphin, the proximity and the contact between objects as main approach. *Airtap* and voice recognition are necessary only in rare situations while playing, just during reasoning tasks that should entail the potential capacity to use it. Most of the times is just the therapist that has to use them, to press menu buttons or similar actions.

In detail, the game is structured as following from the interaction point of view: the educator sets all the settings of the game, using also gestures and vocal commands. Then, once prepared, it gives the headset to the user. Starting from that point on, no more *Airtap* gestures are required. At the end of the game the educator takes back the headset and can save data or change settings using again all type of interactions.

This approach allows users to avoid doing a tutorial specifically just to learn HoloLens gestures and avoids using additional external remote controllers.

All this effort has been done to simplify as much as possible the interaction, thus allowing users play more easily and concentrate just on the tasks to do.

4.2.4 Tangible Avatar

In some games it is present a virtual avatar that represents the alter ego of the player. The avatar can have various usages. It can be used to give hints and explain how to play the game, for example, and it could appear during the game when it is needed. Although important, this is a basic usage.

Another important usage of the avatar is to create a connection between the player and the game. An Avatar helps the player to feel part of the game, especially in those players with NDD. [5][27][28]

The avatar can be present in many different forms. It can be virtual, or it can be real in more traditional old games. Children often feel an intense connection with their best toys while playing.

Therefore, in this application the Smart Dolphin itself has become a real avatar that creates this important connection between the player, the story and the game.

This solution helps with some requirements relative to the realism of the game and the fact that the game and the story should be compelling to attract users.

When during the game the dolphin is touched in some points can emit (through Hololens) some hilarious sounds and effects, in order to make the main character more "alive" to the eyes of the player, that in this way is more involved in the game and spurred to talk with him. Children often speak with toys they love, and they use to humanize them.

4.2.5 Considerations on design choices

In this section it is deepened the discussion regarding the motor and cognitive tasks previously defined, along with some additional design considerations.

Concentration

One of the requirements of the application is to improve concentration skills of users with NDD. Some of these types of users have various difficulties in concentrating into a task for some time.

Considering these difficulties, there have been designed some tasks that try to stimulate the attention of the player.

In particular, the task of monitoring the energy of the Smart Dolphin stimulates the user to keep an eye on the energy value as the game proceeds (Figure 4.13). This task can be activated or deactivated depending on the necessities of the educator.

Apart of that specific task, all phases of the game need some concentration, for example in moving properly to collect the bubble rings. Moreover, some effects are used in particular moments to attract user's attention. Some examples can be when the aura attracts the player or when spatialized sounds suggest the user where he/she should look.

Figure 4.13: when the energy task is active, the energy bar must be constantly refilled eating food

Physical activity and eye-hand coordination

Games have been often criticized for the fact they don't encourage physical activity in people, especially in children. The HoloLens and other devices based on XR could overturn this commonplace.

As it can be noticed throughout some of the design choices, the app focuses especially on the movement of the player to accomplish the basic tasks. This allows to encourage all users do some gentle (but continuous) physical activity, and at the same time it could improve spatial perception and eye-hand coordination in those users having motor impairments.

The alternation of elements to catch and elements to avoid makes the player move, and the fact that bubble rings must be caught with a certain minimum angulation contributes to the movement.

In principle, the game is conceived to be played while standing and moving around the *Aura* during the travel flow game. Anyway, the game can be played also while seated (inside the aura) because it adapts to user height before the match starts.

To track the position of the Smart Toy an image tag attached to the dolphin is being used. This requires maintaining the dolphin in a horizontal position in front of the player, helping in making some additional physical exercise.

When the player needs a rest, he/she can temporarily pass to a mode where it is the position of the camera that is used to catch or avoid the elements.

This allows to satisfy various requirements related to usability and skills improvement.

Spatialized sound and music

Sound is an extremely important part of any multimedia content, therefore it should not be neglected in order to offer a complete experience to the user patient. In games sound can be used in various ways:

- Soundtrack music
- Special effects
- Ambient sound

Depending on the soundtrack and special effects, the mood of the game can completely change. Every soundtrack and every audio effect put in the game should reflect the emotions wanted to transmit in that particular phase of the game.

In order to give users a pleasant experience there have been chosen soundtracks using major scales that typically convey a sense of joy and happiness. In both *Room Exploration Mode* and *Infinity Mode* the soundtracks have these moods, with *Infinity Mode* music being a little faster paced.

In the *Treasure Hunt* part of the *Adventure Mode*, instead, as the gameplay becomes more explorative, it has been used a more intriguing soundtrack to give a little sense of mystery.

With special audio effects it has been used a similar approach, funny cartoon and thematic sounds have been used to emphasize the experience. Some sounds, like stated above in the avatar paragraph, are dedicated to the Smart Dolphin reactions when it is touched in some points. These sounds have been made human-like in order to involve the user in a greater way.

One of the most important things in sound design choices has been to make all sounds spatialized: this feature is suggested by Microsoft and HoloLens game developers to capture user's attention [54][56].

Spatialized sound has been used as a solution to the requirement regarding the orienteering and spatial perception improvement. It has been used as an exercise for users with impairments to try improving their spatial consciousness and concentration. An example can be noticed in the *Treasure Hunt* phase. There have been put spatialized sounds to each key the player must find to open the treasure chest. This means that the user has to find them orienting himself/herself with sound, coming more from one speaker or the other and more or less intense depending on the position of the player and the position of the key emitting the sound.

Also in the travel-flow phase all sounds of all the flowing elements are spatialized. This helps the user to identify where are the elements and where to direct the gaze, increasing the usability of the game.

The effect of the spatialized sound gives also a sense of reality to the game. To improve realism there has been added also a cut-off filter that cuts some frequencies when the water animation rises above the player, creating a realistic and dynamic sound of being underwater. This design choice has been made to let users with NDD benefit from a game both cartoonish and realistic to maintain a connection with the real world.

Memory and reasoning

Basic reasoning is always present throughout all the game and helps the user to stay focused on each task, but main memory and reasoning tasks have been placed in the *Treasure Hunt* phase. In fact, during this phase, basic reasoning and spatial orienteering should work in tandem. This could be a way to improve both more efficiently.

A memory task is especially introduced in the last level of the *Adventure Mode*: in the *Treasure Hunt* phase this time there are no keys to collect to open the treasure chest. There is instead a random password of 4 digits that is generated and attached randomly to one of four paintings spawned in the room (Figure 4.14). A numeric keypad appears if the player approaches the treasure chest, therefore using reasoning and memory skills the user has to understand that a code is needed to open the chest and he/she must find it in the room. Once found, the code has to be remembered and inserted in the keypad to open the chest. A new code is generated each time the third level starts, allowing the therapist to use the exercise for an unlimited number of times.

Figure 4.14: Left-image: second level of the Adventure Mode, two keys must be found to open the chest. Right-image: third level of the Adventure mode, a password has to be remembered to open the treasure chest.

Importance of the story

The story in a game can contribute significantly to the appealing of it, especially if the product is dedicated to young people. Therefore, it can contribute in solving some requirements and giving a sense to the entire game.

It has been decided to create a story that is mostly fanciful, but there have been added some realistic elements to make it more consistent. This has helped also in some other design choices, like deciding which would have been the enemies of the dolphin in the game. Giving a name to the main character can be crucial for the appeal of the story, therefore it has been selected a name that has been considered both fine and a tongue twister, "*Phil the Dolphin*".

Elements of teaching

One of the objectives of the application has been also to leave a "message", a teaching, to its users. Games are sometimes criticized for the content and the message they convey, therefore it has been decided to put teaching bits disseminated during the game.

The most evident teaching bits are the messages that have been put between waves of flowing elements (Figure 4.15). This period of time is conceived to leave the player some time to recover. It also makes the game more dynamic not having all the flowing elements coming like a single wave. Each one of these messages explains in a few lines something related to dolphin's behavior and ocean life in general.

Figure 4.15: Teaching bits examples

Other implicit teaching bits are included in the way the game is designed. The decorations are selected carefully considering the fauna of the oceans: there are corals, various type of typical fishes, sea stars and lot of other elements. Also the fact that sharks are dolphin's enemies in the game comes from reality. In fact, there is evidence of sharks attacking dolphins sometimes, especially if young [47]. With the same approach there have been chosen little nice octopuses as the food that the dolphin must eat to refill his energy bar. Dolphins typically eat cuttlefishes, crustaceans, squids and octopuses. So, these design choices were dictated by real dolphin's behaviors. Similarly, as obstacles there have been put things that shouldn't stay in the oceans, like cans and broken bottles, to educate children to respect the environment.

To better learn some things about oceans and sea creatures, a journey has been spent to the oceanographic park of Valencia (shown in Figure 4.16), the biggest aquarium in Europe, comprising lot of species all over the world. Some of the content learned has been integrated into the application in order to make it more realistic and useful for its users.

Figure 4.16: Oceanogràfic Valencia.

4.3 UI

Inside the *ATOF* application there have been used two types of user interfaces, both classical and world-anchored:

- **Classical UI:** composed by menus leveraging the classical interaction paradigm involving buttons. These types of menus have been made always facing and following the player without head-locking them (*Tag Along* behavior) to avoid overwhelming, as per Microsoft design guidelines [53]. An example can be seen in Figure 4.17.
- **World-anchored UI:** this type of menu, shown in Figure 4.18, is anchored and integrated in the room. In *ATOF* it has been placed into the Playfield and it is used during the game/training. It is composed by a banner indicating the score of the player and two indicators respectively indicating the current health and energy of the dolphin during the experience.

In XR applications is generally preferable to use classical UIs just for complex views, and world anchored UIs whenever possible, because they leverage the characteristics of the environment giving a more sense of realism [45].

For this reason, during the game only world anchored user interfaces are used. Instead, in the main menu, due to the presence of lot of details to visualize and parameters to customize, there have been implemented the aforementioned classical UIs.

The UI has been designed to be as self-explanatory as possible. An example is the fact that during the game the indicator regarding the health of the player is represented by a heart changing both color and pumping rhythm depending on its value. Another example could be the fact that above the energy bar of the world anchored UI it is shown the food object that needs to be caught in order to increment the energy; so, when that certain object appears, it should be clear what it does. Some messages and tips occasionally suggest what to do during the experience.

Figure 4.17: Classical UI

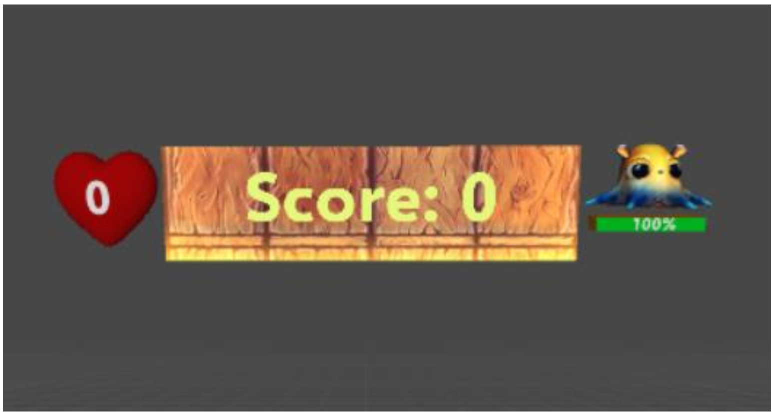


Figure 4.18: World-Anchored UI

HoloLens allows to obtain different degrees of blending between real and virtual world. This feature has been exploited during the design of the visual interface to make it more intuitive. As shown in Figure 4.19, the degree of involvement can be customized leveraging on the textures transparencies of the floor, the walls, the tables and the ceiling. A design choice has been to use predominantly opaque textures, but the contact with the world is however maintained because the device doesn't isolate the user.

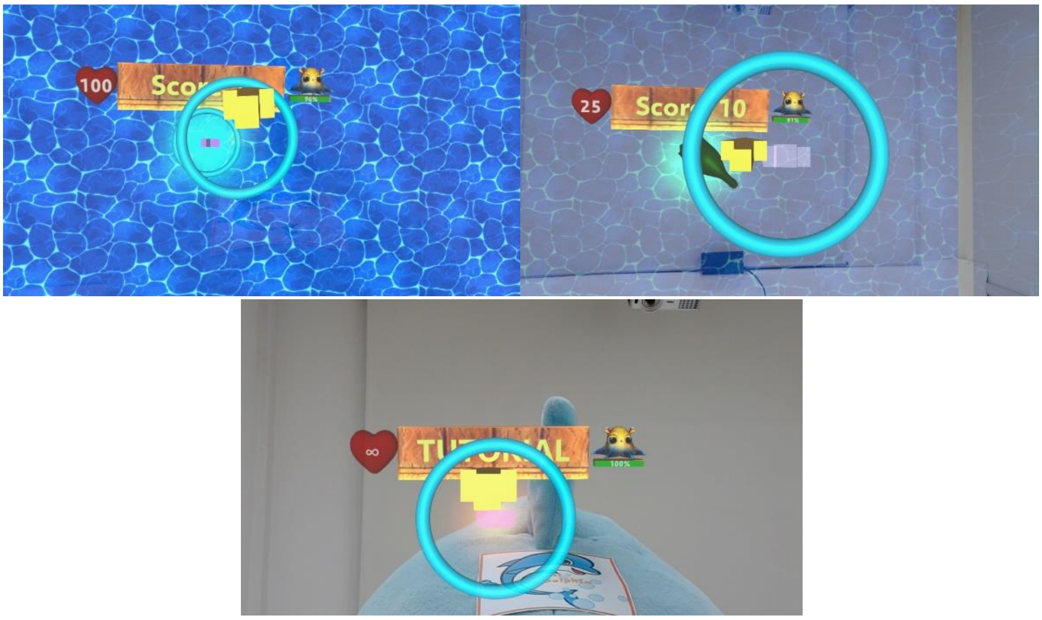


Figure 4.19: Textures degree of transparency can customize the involvement of the user.

4.4 Scenarios

Tutorials with streaming and dolphin feedbacks

Suppose that the user patient, Elliot, has never tried the application.

An hour before the therapy starts, the therapist begins setting up the hardware equipment, composed by the Hololens, the Smart Dolphin, a notebook and the dedicated offline router. He connects the dedicated router to a power socket. The notebook, the Hololens and the Smart Object connect automatically to the Wi-Fi LAN of the router. Finally, he starts both the server on the notebook (just double clicking it) and the *ATOF* application on the Hololens. He selects one of the two **tutorials** (the basic one) and uses the vocal command “Streaming On” so he can do the streaming through the Hololens Application on his notebook. In fact, since Elliot is the first time that uses the application, he wants to observe in detail what he will do.

The therapist puts the headset on Elliot’s head. Elliot, his patient, sees the room completely transformed and decorated with sand, water and corals. He also notices an aura and a sound coming from it, as well as a message inviting him to get the dolphin and go inside it. When Elliot goes inside it, the Smart Dolphin moves the eyes/mouth, a countdown starts and a generator appears. Once the countdown finishes an arrow appears in front of Elliot and some bubble rings start going towards him. Once collected them using the arrow, the generator moves a bit and the rings start being generated again.

In the meanwhile, the therapist is seeing how the boy is performing through streaming. Every time Elliot gets a ring correctly, a sound is played and the feedback leds of the dolphin become green for one second. If instead Elliot gets them wrongly, the leds of the dolphin become red for one second.

When the patient finishes taking correctly enough rings, the eyes/mouth of the Smart Dolphin moves again and the tutorial finishes. The therapist takes back the headset and decides if the user needs to do another time one of the tutorials.

Room exploration

Suppose that the user patient, Darlene, has never tried the application, and that the hardware equipment is already set up.

The therapist puts on his head the headset. For his patient Darlene he wants starting doing a more easy and relaxed activity due to the fact that she is a bit tense and problematic the day of the therapy. The therapist from the menu of the application selects the button “Explore the room” and puts the headset on Darlene’s head, then he follows her via streaming.

Darlene sees the room completely transformed and decorated with sand, corals and fishes. She starts going around and she notices that approaching some funny characters attached to the walls, they start moving. Instead, when she goes away, they freeze. She starts playing with this mechanism and then goes exploring all around the room to notice all the little creatures inside the mixed reality experience. A pleasant music plays on the background. Suddenly also a water effect appears, going from the bottom to the ceiling, along with some seagulls appearing at the center of the room and flying away. The decorations now have changed, and Darlene can explore again the room.

When Darlene becomes more relaxed, the therapist takes back the device and thinks about preparing the tutorial or the Infinity mode.

Infinity Experience with in-game streaming deactivation

Suppose that Elliot has already done with success both the tutorials, and that the hardware equipment is already set up.

The therapist puts on his head the headset and goes to the Infinity Mode settings. He customizes the Infinity experience setting three waves of elements composed by 5 rings and activates teaching bits that will appear between those waves explaining some curiosity about the oceans. Then he selects the Infinity mode and puts the Hololens on the head of the patient.

Elliot will see, as usual, the aura inviting him to enter with the dolphin. Once entered, the countdown starts, the generator appears and the rings start flowing, each one with a random rotation, therefore Elliot to collect them needs to rotate and move himself a bit to rotate the usual arrow appeared in front of him towards the direction of the rings.

The therapist sees that the patient is performing well, therefore he deactivates the streaming using the vocal command “Streaming Off” (that, in turn, reactivates the image tracking) and invites the patient to directly (and more precisely) use the Smart Dolphin to collect the rings.

Once the experience finishes the therapist takes back the headset, inserts the patient’s username and saves the data of the training.

In conclusion, he thinks about eventually restarting the Infinity mode adding some additional tasks like obstacles-avoidance or energy refilling.

Adventure Experience with only dolphin feedbacks

Suppose that Elliot has already done with success the Infinity Mode a certain number of times, and that the hardware equipment is already set up.

Thanks to the therapies, Elliot starts improving a bit his motor capabilities. He has learned to stay straight with his back and head in order to collect the rings properly, and the hands movements are more precise during the trainings.

The therapist puts on the headset and this time decides that he wants to make the patient do also some cognitive tasks, so he selects the Adventure Mode that integrates both motor and cognitive exercises. Then puts the headset on the patient and uses the vocal command “Streaming Off” because he prefers monitoring the boy staying near him and using the feedbacks coming from the Dolphin (green/red leds). Moreover, he wants Elliot to use directly the Smart Dolphin (the tag) to collect the rings.

Elliot this time has to complete various tasks. In fact, after having completed the part where the rings flow towards him, the treasure hunt begins, and the room is adorned with various decorations. Among all the objects Elliot notices a treasure chest, but when it approaches, a message saying “Find the Key” appears. Paying some attention to the sounds, Elliot realizes that there is just a sound continuously repeating in the background. It is a spatialized sound, so moving the head Elliot recognizes the provenience of it. The boy goes towards the sound and finds the key. Then, coming back to the treasure chest he opens it and takes the map inside, completing the level.

When the experience ends, the therapist puts the headset on, inserts the patient's username, and saves the data of the training.

Consulting the data

Suppose that Elliot, Darlene and Angela are three patients that have already done with success some trainings (Infinity or Adventure Mode) a certain number of times.

The therapist, after one month of training, wants to see if the patients have improved some of their skills. He opens the *ATOF* application and goes to the statistics menu to have a quick overview of all the trainings done. He sees parameters like the rate of caught rings, rate of avoided obstacles, error tolerance, time to complete the treasure hunt, and many more.

He wants to see additional details and print the results, therefore the therapist quits the application and goes into the application folder to get the "dataMatches.json" file, containing all the detailed statistics in a readable format. He prints the file and analyses it along with the observations he autonomously annotated on his notebook.

5 Implementation

For an application using this type of technology, the implementation phase requires lot of testing in order to obtain a reliable software. An iterative development style has been used, where feedback, debugging and reimplementation have played an important role.

In this chapter are presented the tools used, the hardware architecture, the software architecture and all the building blocks from which the application is composed. Problems arose during the implementation or testing will be discussed along with their solution or mitigation.

5.1 Implementation Tools and Languages

Since the application involves different and specialized tools, it was necessary to integrate various technologies in order to ensure consistency. The main tools used to create the application have been Unity, Visual Studio, Vuforia and the Mixed Reality Toolkit.

5.1.1 Unity

Unity [76] is a cross-platform real-time engine developed by Unity Technologies. As of 2018, the engine has been extended to support 27 platforms. The engine can be used to create both three-dimensional and two-dimensional games as well as simulations for its many platforms. There is the "Personal edition" that is free of charge, if the revenue per year does not exceed $100K.

It is one of the simplest frameworks for building powerful and efficient X-reality experiences (VR, AR, MR). Among the supported platforms there is also Hololens (Windows Mixed Reality platform) and the usage of Unity software is recommended by Microsoft for the development of holographic experiences. For these reasons it has been chosen for the development of the system.

Unity has got one of the largest communities of developers in the world. In fact, being a framework capable to support a great number of platforms has given Unity lot of experienced developers able to offer a great assistance.

The main programming language supported by Unity technical documentation is C#. There was support also for Boo and Javascript, but they were deprecated in favor of aforementioned one. The engine offers a primary scripting API for both the Unity editor and games, as well as drag and drop functionalities.

All the building blocks of the application, tasks, scenes, data collection and UI have been made with Unity. Graphics, models and sound have also been integrated in the game using this framework.

To allow writing C# scripts Unity works in tandem with either Visual Studio or Monodevelop IDEs. Usually Visual Studio is preferred since it is more powerful.

For the Hololens 2 Microsoft has announced the support also by the Unreal Engine, another popular cross-platform framework. Nevertheless, Unity will still be a very good choice because it allows to control more easily all the aspects of the project as a whole, that is a very important quality for single developers or small indie game teams.

5.1.2 Mixed Reality Toolkit

The Mixed Reality Toolkit (MRTK) [51] is a Microsoft Driven opensource project providing a set of foundational components and features to accelerate Mixed Reality app development in Unity. Microsoft guidelines recommend the usage of this toolkit to develop apps for Hololens. It provides basic and advanced features as an easy to use SDK to get easily started. Among the included features are comprehended an input system, voice commanding, gaze, selection, interactions and the spatial understanding. The MRTK is constantly under development and a forum with experienced developers is available to seek some support. The toolkit has to be integrated in the Unity project and offers also some preset configurations useful to start easily the development of the application.

5.1.3 Visual Studio

Microsoft Visual Studio [52] is an integrated development environment (IDE) from Microsoft. It is used to develop computer programs, as well as websites, web apps, web services and mobile apps. Visual Studio uses Microsoft software development platforms such as Windows API, Windows Forms and the Universal Windows Platform (the one used by Hololens). It can produce both native code and managed code.

The most basic edition of Visual Studio, the Community edition, is available free of charge.

Visual Studio includes a code editor supporting IntelliSense (the code completion component) as well as code refactoring. The integrated debugger works both as a source-level debugger and a machine-level debugger.

It can work in tandem with Unity and it is the recommended way to code scripts on it. Moreover, VS is necessary to deploy the application on the Hololens.

This IDE supports more than 30 different programming languages, but as previously said the recommended language to code for Unity is C#.

5.1.4 Vuforia

Vuforia [77] is an augmented/mixed reality software development kit (SDK) for mobile devices that helps in the creation of augmented and mixed reality applications. It uses computer vision technology to recognize and track planar images (Image Targets) and simple 3D objects, such as boxes, in real time. This image recognition capability enables developers to position and orient virtual objects, such as 3D models and other media, in relation to real world images when they are viewed through the camera of a mobile device. The virtual object then tracks the position and orientation of the image in real-time so that the viewer's perspective on the object corresponds with the perspective on the Image Target. It thus appears that the virtual object is a part of the real-world scene.

The Vuforia SDK supports a variety of 2D and 3D target types, although 2D image targets are better recognized and tracked.

This SDK derives from OpenCV (Open source computer vision) that is a library of programming functions mainly aimed at real-time computer vision. Some of the example applications of OpenCV are gesture recognition, image recognition, motion tracking, facial recognition and human-computer interaction

Unity in its last versions supports Vuforia, that can be used for a large quantity of platforms, Hololens included.

For the *ATOF* application it has been decided to leverage the Vuforia SDK because it was needed to track the movement and the rotation of the Smart Dolphin in real-time, and Vuforia has got the more advanced capabilities in this sense. In fact, it can detect position and rotation of the targets in a smoother way with respect to the competition. It can also detect colored images apart of markers or QR codes. This could enhance the likability of the application especially for users with NDD and children.

The only alternative for Imaging Recognition with Hololens was *Microsoft Poster Tracker*, but this isn't designed to do a real-time tracking with moving objects, as the name also suggests. It aligns a virtual object with the position of a real one, then additional movements are allowed with a manual alignment done with vocal commands. It can be used in cases where the developer wants to make it appear static virtual objects on top of static real ones, like posters.

5.1.5 Languages

The languages used for the application implementation have been:

- **C#:** [55] it is a general-purpose, multi-paradigm programming language encompassing strong typing, lexically scoped, imperative, declarative, functional, generic, object-oriented (class-based), and component-oriented programming disciplines. This language is intended to be a simple and modern programming language. It features automatic memory management and it is particularly suitable for deployment in distributed environments. Through specific C# there have been built all the tasks of the application, including the different behaviors of all the collectable interactive flowing elements the user has to catch or avoid during the training. It has also been used to manage the saving of the data relative to the different matches and most of the interactions between Hololens and the Smart Object. C# has been used to program the application logics and all the functionalities of the *ATOF* system.
- **Python:** [66] it is an interpreted, high-level, general-purpose programming language, supporting multiple programming paradigms, like the object-oriented, imperative, functional and procedural ones. It has a design philosophy that emphasizes code readability and clear programming. It features a dynamic type system and automatic memory management. *Flask* [19] is instead a micro web framework written in Python that allows to build simple and lightweight web applications. It is classified as a microframework because it does not require particular tools or libraries. In *ATOF*, Python has been used to create (together with the Flask web framework) an intermediate server to manage the communication starting from the dolphin smart object and arriving to the Hololens.
- **JSON:** JavaScript Object Notation (JSON) [38] is a language-independent *data format* (not a programming language) that uses human-readable text to transmit data objects consisting of attribute-value pairs and array data types (or any other

serializable value). JSON has been used in *ATOF* in two situations. First, for sending commands for the interaction involving the Smart Object and the Hololens, leveraging HTTP. Second, for saving the data of the different matches of each user patient.

5.2 Hardware architecture

The *ATOF* system is designed to work either having the *full hardware equipment* or just having a minimum hardware equipment. Of course, having the full equipment greatly enhances the user experience, but the application has been built to be flexible enough to work well anytime.

To obtain the best experience using ATOF, here it is the *full hardware equipment*, described component by component. A visual overview of the equipment and the communication among those components can be seen in Figure 5.1.

- **Microsoft HoloLens headset:** the main component of the equipment, including all the mixed reality capabilities like sensing the environment, anchoring virtual objects to the real world and transforming the aspect of the room where it is used. This is the component where the application runs. The HoloLens headset includes a clicker that would simulate the "tap" gesture, but it isn't needed, especially during the game tasks.
- **Smart Object Dolphin:** this smart object it's not a purchasable product, in fact it is a simple soft toy (plush) that has been modified with additional components, leds and microcontrollers in order to make it "smart", therefore capable of full interaction. APIs have been exposed so that the interaction with the dolphin can be performed through HTTP REST requests. The commands available include turning on/off some leds, moving the eyes and the mouth of the dolphin, and many more. Finally, the smart object is also capable to send events, in particular three types of communication methods are reported in the Table 5.1.
- **Router or Smartphone hotspot:** the application can work in every LAN, but a dedicated router is preferable especially when doing experimentations in therapeutic centers, due to the fact it can be preconfigured speeding up the setup time. The router will manage the communication in both directions, coming from the Smart Object towards the HoloLens (through an intermediate Python-Flask server) and going from the HoloLens towards the Smart Dolphin (more details on this mechanism will be explained later in the software architecture section).
  An alternative to the usage of the router can be a smartphone set like a Wi-Fi hotspot. Some testing has been done with this configuration but with some type of smartphones it gave problems. Therefore, it could be preferable using a dedicated router.
- **Notebook:** a notebook (or a pc) is mostly required for two reasons. First, to do monitoring (through the Microsoft HoloLens streaming app) in order to see what the user is doing in the game. Second, in the notebook it should run the intermediate server capable of receiving events from the Smart Objects and forwarding them to the HoloLens application.

Types of communication - Smart Object → Other device	
Type	**Description**
TCP events	Each time an event happens (like a touch on the dolphin's head, or a touch on one of the fins) an event is fired by the smart dolphin to a certain (customizable) IP number present in the same LAN. The protocol used in this case is the TCP (Transmission Control Protocol), that is considered reliable because it checks to see if everything that was transmitted was delivered at the receiving end (it may not have been due to packet loss). TCP allows for the retransmission of lost packets, thereby making sure that all data transmitted is (eventually) received. The reliability has a cost, it makes the communication slower, but this delay cost is negligible considered that this interaction happens in a LAN. This is the method that have been used for the *ATOF* system.
UDP streaming	This type of communication is faster but can be subject to a greater data loss. It opens a streaming channel continuously sending data. It works well to obtain almost real-time data about the accelerometer or gyroscope, for example, but it doesn't work well for more rare events like the touch on head/fins because for most of the time the UDP streaming channel would continuously send lot of garbage data indicating that touch didn't happen yet, therefore wasting resources.
TCP ping	With this method it could be sent a ping to the Smart Object asking for its state, and the Smart Object would eventually respond. This could be also used for diagnosis and test purposes.

Table 5.1: Smart Object types of communication, going towards other devices

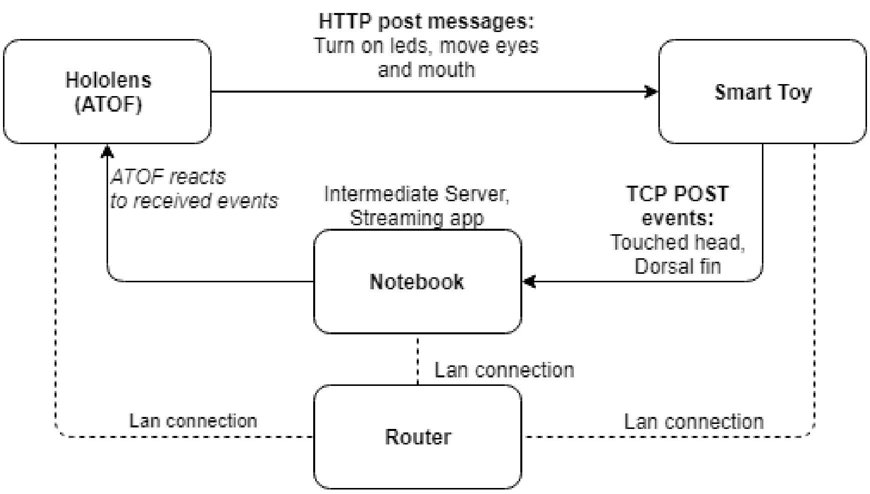


Figure 5.1: Full hw equipment and communication through components

As previously said, this is the *full equipment*, but the application can work also without most of the aforementioned hardware. In fact, it can run also with just the HoloLens and the Smart Dolphin (sacrificing the communication between the two), and it can even work using just the HoloLens. In this last case it will be taken into consideration the position of the head instead of the position of the Smart Object to complete the tasks. These details will be discussed later in the software architecture section. Lastly, one more thing to mention is the fact that *ATOF* doesn't require an internet connection to work, as it is needed only a local communication over a LAN.

For information regarding the setup operations, please refer to the manual at the end of the document.

5.3 Software architecture

5.3.1 Native application

From the software perspective, *ATOF* is a native application for HoloLens. In fact, Unity is a multiplatform framework capable of building native solutions. In the case of ATOF, the building process has been made using the currently recommended .NET scripting backend, and as a result Unity created a native C# Visual studio project that could be deployed on the headset as a Universal Windows Platform (UWP) application.

Inside this application it is already contained all the necessary logic to run the system and to manage most of the communication interactions. Along with the headset the application can run in principle without any additional components (*minimum required equipment*).

Creating a native application for sure offers a boost in terms of performance and efficiency. This is one of the motivations why most of the XR (AR/MR/VR) experiences are delivered as native apps. In the last years a new distribution model known as Software as a Service (SaaS) became popular and some applications migrated from being native desktop apps to cloud-served solutions, but the adoption of this new distribution model mostly depends on which type of functionalities and requirements the application needs. In the case of *ATOF*, and many other MR experiences, it didn't make much sense to use a web application approach because of the nature of the system.

Moreover, a web application approach would have introduced an additional and useless constraint, that is, there would have been a strong dependency on the internet connection. *ATOF* even in its full equipment mode only uses local communication to manage interactions with the Smart Object, therefore it can be used even when an internet connection is not available, extending the possibilities and places of its usage.

Another advantage of not using a web application approach is the fact that typically web apps have access to a limited set of hardware features, plus they can suffer from a broader attack surface than installed native apps, thus being more subject to security issues.

5.3.2 Mixed Reality environment and components

It has been used a mixture of components supplied by the Unity Editor and some specialized ones provided by the Mixed Reality Toolkit (MRTK, aka "HoloToolkit") particularly dedicated to the HoloLens development.

The Unity scene that resulted from the development is composed by some main components described in Table 5.2 and shown in Figure 5.2:

Main components of the Unity scene	
Type	**Description**
Camera (integrating image tracking)	Entity that defines from which perspective the user views the scene. In the application this component is provided by the MRTK toolkit, that supplies specific functionalities and parameters dedicated to the HoloLens. There have been added also some extra functionalities to this Mixed Reality Camera. One of the most important is the possibility to track the position and rotation of the image tag attached to the smart object leveraging the image processing capabilities provided by the Vuforia SDK integrated into the project. Other functionalities comprehend a directional light (light source infinitely far away shining from a direction) to slightly enhance the illumination of the portion of the environment seen by the user, and a collider (an invisible shape) capable of detecting collisions with other objects in the scene.
Cursor	The cursor is another useful component provided by the MRTK toolkit and it is strictly related to the Camera. It represents in every moment the direction of the camera, thus its position depends on the rotation and position of the headset. The default cursor is a white circle and it allows the user to perform gestures. It must be positioned over interactive elements before making an *AirTap* gesture in order to perform an action.
Input MRTK Managers	Components provided by the MRTK toolkit in order to detect various inputs. Examples are gestures as the *AirTap* (similar to pinching) and *Bloom* (opening the hand from the bottom). Other examples are the voice keywords, recognized by the *Speech input handler*.
Spatial mapping and processing components	These are very important modules of the application. They are supplied by the MRTK toolkit and allow to sense the environment and build a mesh (a polygonal representation) describing the room where the headset is placed in. This mesh is then processed to obtain the various surfaces representing the room, like the floor, tables, walls and ceiling. Finally, to those plane surfaces are applied textures to enhance the blending of the virtual environment with the real world.
Managers components	There are various component managers that take into account all the logic of the application, like the game tasks, the saving of the data, the menus, the generation of decorations, the sound and the interactions with the Smart Object. Examples are the Game Controller, Data Controller, Sound Manager among the others. Being unique components inside the projects, they have been implemented using the Singleton pattern, guaranteeing that for a certain class is created only one instance and giving a global access point to it.

Objects, Playfield and decorations	Dynamically added into the scene during the experience. The Playfield, necessary to play the game, is added just one time at the start of the application after the room has been scanned, then it remains inside the scene until the application is closed. The other objects and decorations are virtual 3D objects (cubes, spheres, planes and more articulated models) placed all around the environment considering the extension of the room. In this way the user can walk around and interact with most of them. Some other objects instead of being anchored to the world assume a relative position with respect to the camera. An example is the starting menu, that smoothly follows the player.

Table 5.2: ATOF, main components of the Unity scene

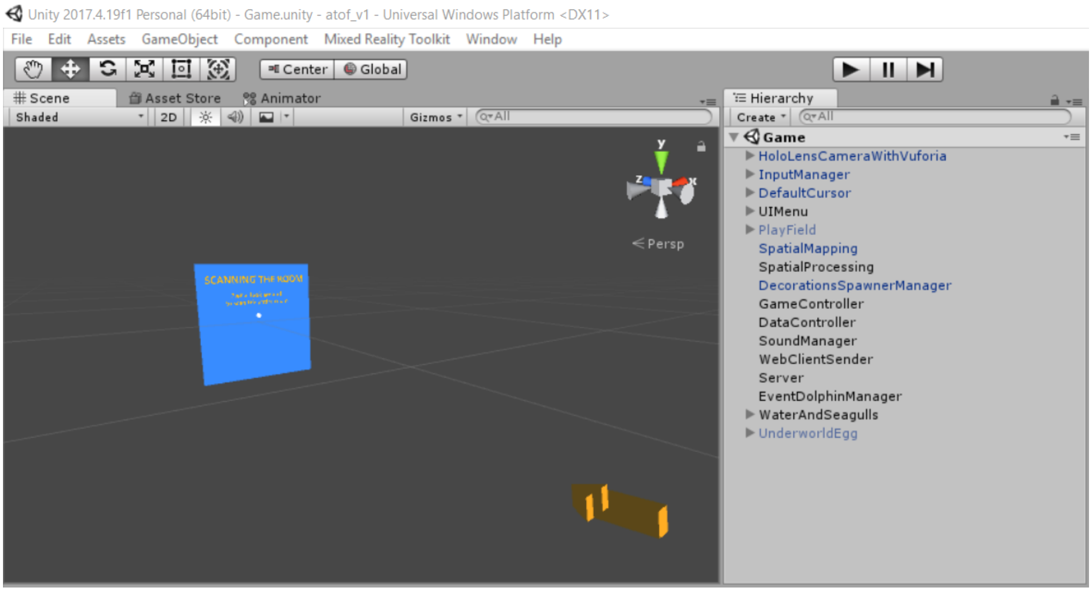


Figure 5.2: Unity scene

As it can be deduced, most of the elements of the scene are dynamically added at runtime. This is necessary because the application has to adapt to the room where it is launched, furtherly customizing the experience at each run.

Another thing to notice is the absence of artificial light components in the scene (except for the directional light attached to the camera that have been used just to slightly enhance the experience). In fact, most of the light is given by the real environment, therefore there isn’t the need to add an *ambient light* globally affecting all the entities in the scene. To be clear, a *directional light* represents a light source that is infinitely far away, but shining from a specific direction, like the sun. An *ambient light*, instead, globally affects all entities in the scene in all directions and it is useful to mimic indirect lightning, which in computer graphics applications allows to avoid that some areas of the scene are shown as totally black.

5.3.3 Interaction between Hololens and the Smart Object

The communication between Hololens and the Smart Object has been implemented in both directions, that is, from Hololens to the Smart Object and from the Smart Object to Hololens.

Communication Hololens → Smart Object

In this case there have been used HTTP REST requests in order to interact with the Smart Object. In fact, the Smart Dolphin exposes some APIs to receive POST requests containing a JSON encoding a command to make the Smart Object react in some way, for example turning on/off certain leds or moving eyes and mouth.

Here the Hololens acts as a Client and the Smart Object acts as a Server (Figure 5.3).

Figure 5.3: communication from Hololens to the Smart Object

To realize this type of communication it has been leveraged the *UnityWebRequest*, that is an object used to communicate with web servers and handling the HTTP flow. *Promises*, a way to write async code that still appears as though it is executing in a top-down way, have been used to improve the code readability and to avoid *Callback hell* and the *Pyramid of doom*, two poor coding practices.

HTTP POST requests, directed to the LAN IP number of the Smart Object, have been used to turn on for one second some green or red leds depending if a ring has been successfully collected with the right rotation or not by the player. In addition, at the start and at the end of the experience a command is sent to move both eyes and mouth of the Smart Dolphin.

An example of one of the JSON commands that can be sent to the Smart Object is showed in Figure 5.4, it turns on some leds on the head. A visual example is shown in Figure 5.5.

```
{
    "requestType": "set",
    "lightControllerSetter":
    [
        {
            "code":"parthead",
            "color":"#00FF00"
        }
    ]
}
```

Figure 5.4: simple example of a JSON command contained in a POST http request (turn on leds)

Figure 5.5: the user wrongly caught a ring, therefore red leds have been turned on

Communication Smart Object → Intermediate Server → HoloLens

In this case, instead, there have been used TCP events (please refer to the HW architecture paragraph for more information) to receive events coming from the Smart Object and react inside the HoloLens application with sounds and effects. In particular, there have been managed the *touch* on the **head** and on the **dorsal fin** of the Smart Dolphin.

Here the HoloLens acts as a Web Server and the Smart Object acts as a Client (Figure 5.6).

This type of communication required a bit more attention, in fact it required an Intermediate Server to act between the two entities.

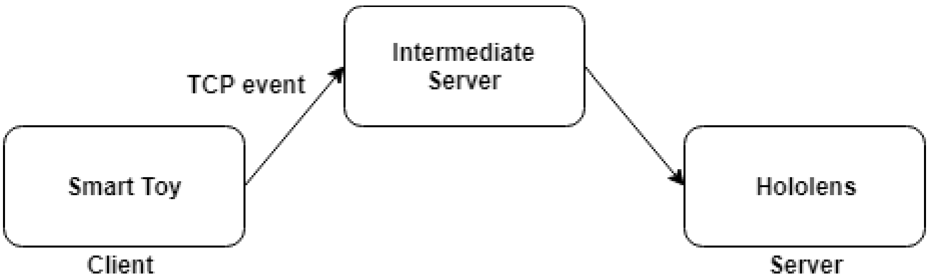


Figure 5.6: Communication from Smart Object to Hololens (passing through an intermediate server)

It has been decided to use an intermediate server to manage this communication because direct one would have had two major problems:

1) *HttpListener* (a class providing a simple, programmatically controlled HTTP protocol listener) was working on Unity but not on the HoloLens. More in detail the problem was this: UWP applications from the SDK version 16299+ now support .NET Standard 2.0 and *HttpListener*, but still there wasn't the possibility to use it because there were problems in building for the Universal Windows Platform (UWP). In fact, there was an attempt to use the .NET scripting backend recommended by Microsoft tutorials, but when building, the latest .NET packages weren't picked up. Instead, there was a downgrade of the .NET version where *HttpListener* isn't implemented. So, it has been concluded that at the moment the .NET Standard 2.0 isn't offered as a

compatible API level and that new things which came along, like SDK 16299 with its support for .NET Standard 2.0, didn't get implemented by Microsoft in the .NET Scripting Backend for Unity.

2) *StreamSocketClass* (a class supporting network communication using a stream socket over TCP in UWP apps) was working but with problems: some TCP events coming from the Smart Dolphin were correctly received while others weren't.

After trying different solutions, it popped out that the Intermediate Server, receiving messages from the Smart Dolphin and sending them to the HoloLens, was the best solution.

The intermediate server has been made with Flask because it is a simple and lightweight web server gateway interface (WSGI) web application framework. It is in charge just to resend dolphin's TCP messages towards the IP number of the HoloLens. Then in the application the POST message is analyzed, the JSON is parsed, and the respective action is taken.

An example of the JSON contained in the TCP event sent by the *Smart Dolphin* is shown in Figure 5.7.

```
{"events": [{"typ": "touch", "val": "5", "act": 1}]}
```

Figure 5.7: example of the JSON contained in a TCP POST event sent by the SmartToy (touch of the dorsal fin)

If the user presses the head or the dorsal fin of the *Smart Dolphin* then some sounds and effects are played. Moreover, during the concentration task when the energy bar is decreasing, these two actions slightly increment it, as well as when the Dolphin eats some food.

5.3.4 Experiences implementation

There have been implemented three experiences for the users. At the start of the application the room is scanned for some time (typically half a minute) by the Spatial Mapping component in order to extract a polygonal mesh of it. Then this mesh is processed and surface planes objects representing walls, floor and ceiling are obtained through the Spatial Processing component. Textures are added to those surface planes only at the end, if any.

The Playfield containing the game area is then placed on the floor, using a *Raycast*, at the minimum distance from the user and avoiding obstacles like tables. At this point a water effect and some decorations appear and the main menu is shown in front of the player along with a soundtrack. Before starting an experience, the therapist can change the settings and can move the Playfield to another position, if necessary. The movement of the Playfield has been implemented in a way that the therapist can simply look at the floor placing the cursor in the desired area and he/she can *AirTap* or say the vocal command "*Move here*" to perform the action. Leveraging the *Raycast*, the position and rotation are then updated, and the Playfield is positioned in front of the user.

At this point the therapist can start one of the three experiences. After having made all the configurations he/she can put the headset on the head of the patient and start observing the user through streaming and feedbacks.

5.3.4.1 Experience: Explore the room

This type of experience, as said, is meant to let the player go around the room and interact with the different elements decorating it. Can be useful especially for those user patients unable for some reason to do the other experiences.

The decorations of the room can be renewed either by pressing a button in the mixed reality environment or sending a command from the notebook. Each time the decorations are renewed an animation with some water starts from the position of the floor and reaches the ceiling, along with some seagulls above the user that fly away and a sound of water with an occluded effect (cutoff frequency) dynamically applied when the Hololens Camera is "underwater".

Two algorithms have been mainly implemented for this experience. The first one for creating and putting some dynamically animated GIFs at the center of each wall that react moving themselves when the player is sufficiently closer to them. The placement of those elements on the walls leverage the normal of each wall and a *List* object containing the already used walls.

The second algorithm, described in the following paragraph, is the one for generating random non-overlapping decorations (seaweeds, rocks, fishes, and many more) at random positions on the floor.

Algorithm for random generation of non-overlapping objects in the room

The function has been implemented as a Unity Coroutine in order to simulate concurrent execution thus allowing the application to continue doing other processes in the meanwhile.

A *List*, containing all the objects to spawn, is given to this function, along with a *Boolean* indicating if there is the necessity to shuffle those objects or not. Then the dimensions of the floor are calculated, and a random position is chosen inside this area. At this point still are taken into consideration the local coordinates of the floor, in fact this is necessary for calculating the correct dimensions of it. This potential spawn position is then transformed from the local space of the floor to the world space (that has fixed axis). This step, where it is considered the local space of the floor, is useful because sometimes HoloLens detects the floor slightly rotated around the up-axis and avoiding this step would result in wrong calculations of floor dimensions (world axis would be used) causing some of the objects being spawned outside the virtual floor.

Now, to prevent the overlapping with other already spawned objects, an overlapping invisible sphere can be created around the potential spawn position with a certain radius. All the objects colliding with this sphere that belong to a certain layer (in this application it has been defined a "*FloorObjects*" layer) are inserted into an array and are analyzed to verify if the object that is going to be spawn effectively overlaps or not with the objects already present in the scene. If it overlaps, a new attempt of spawning the object occurs (using a new random position), until a maximum number of tries. If instead it doesn't overlap with any of the objects already present in the scene, the new object is spawn.

Depending on the room size, it may happen that some decorations aren't spawn, but this is not a problem being just decorations, it is even a wanted behavior because in this way the user can see different decorations at each experience.

Important objects (like the ones present in the Treasure Hunt game) instead are always spawn. In fact, if there isn't any potential random spawn position (maybe because the room is too small) they are generated anyway, near the user.

5.3.4.2 Experience: Infinity Mode

This experience is the one fully customizable from the therapist, going in the proper menu before starting the game. The customizable parameters allow, for example, to play with four generators, as it can be seen in Figure 5.8. These preferences on Hololens are saved in a *.dat* file (with a JSON-like structure) inside the application folder, while on windows desktop (during the development with Unity) they are saved in the registry.

Figure 5.8: customized Infinity Mode. Four generators active and obstacles task included. A smashed can has been generated and flows towards the player that has to avoid it.

The *Infinity Mode* leverages different components of the application: the *Playfield*, the *Aura*, the *Playfield Boundary*, the world-anchored UI, the generators and all the flowing elements.

In particular, the *Aura*, the *Playfield Boundaries*, the world-anchored UI and the generators are child of the *Playfield* object (Figure 5.9), in this way when the *Playfield* is repositioned in another place in the room then all these components positions are updated as well.

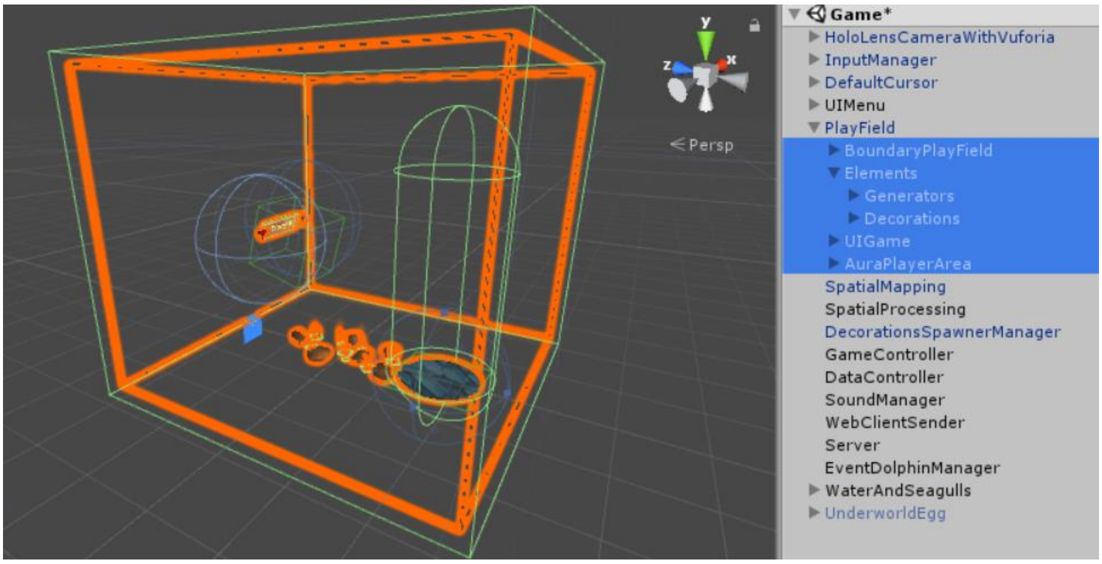


Figure 5.9: child objects of the Playfield, moved along with it when repositioned (Unity editor)

The good functioning of this *Travel-Flow phase* depends for a good part on these elements.

World-anchored UI

As per Microsoft design recommendations the in-game UI has been anchored to the world, as already said. It contains information regarding the score, the energy and the health of the player, along with some audio sources emitting spatialized sounds to attract user's attention. At the start of the game, for a couple of seconds, the world-anchored UI sets its position depending on the position of the user's head, allowing players of different heights to play comfortably.

Aura

The *Aura* mechanism works since the start of the *Infinity Mode*. The particle effects representing the aura are activated and recall the player inviting him/her to go inside it. The aura can detect when the player is inside using an invisible collider (green capsule in Figure 5.9) triggered by the user's movement. When the player is inside the *Aura* and the *Smart dolphin* is detected by the HoloLens camera, a countdown starts and the particles of the aura are deactivated.

Once the countdown ends and the elements start being generated, the *Aura* mechanism works a bit differently. If the player goes out of the *Aura* to avoid an obstacle, a Coroutine function starts counting how much time the player is remaining out of it. If this timer goes to zero then for each extra second the player loses a health point, until he/she returns inside it.

The *Aura* mechanism is dynamically activated and deactivated at the start and at the end of the *Infinity Mode*.

Playfield Boundary

During the game, the *Boundary Playfield* (the big green collider surrounding the *Playfield* in Figure 5.9), can detect if a flowing element is going out of its boundaries. This allows to deactivate those elements that are no longer needed for the game. When an important element is deactivated some special particles effects are visualized, the sides of the boundary blinks for some seconds and a sound effect is played.

Algorithm controlling the Infinity Experience

This is the algorithm in charge of managing the generation of all the flowing elements, including bubble rings, obstacles, sharks, food and powerups, depending on the tasks and parameters activated.

Just before this function is invoked, some objects called “generators” are positioned in front of the player. Those generators are the components from which the new spawn elements will start flowing after being generated.

All the flowing elements are managed with an *Object pooling pattern*. This is a software creational design pattern that uses a set of initialized objects kept ready to use, a "pool", rather than allocating and destroying them on demand. Therefore, all the elements regarding the I*nfinity Mode* are created at the start of the application and just activated/deactivated dynamically when they exceed the *Playfield Boundary* instead of creating/destroying them. This allows avoiding waste of resources.

The function spawning the flowing elements is implemented as a long Coroutine selecting randomly one of the possible elements to be spawned, depending on the tasks activated. At the same time, updating some timers, it takes into consideration also how much time passed since the last food and powerups were generated, thus balancing the gameplay in case of necessity.

After spawning a flowing element, the function waits some time, and the same occurs at the end of each wave of elements. In fact, all the spawned elements are divided per waves in order to let the player rest for some seconds. In this spare time, if activated, the teaching bits appear telling the user patient some curiosities about the oceans.

If before starting the game the energy task has been activated, then another additional Coroutine is activated concurrently with the aforementioned one in charge to randomly spawn flowing elements. This additional Coroutine progressively decrements the energy value of the dolphin, and this can be seen observing the world-anchored UI. This decrement temporarily stops when a learning tip appears between waves, in order to not disadvantage the player. Food, represented by little flowing octopuses, can increase the energy value, as well as pressing the dorsal fin or the head of the Smart Dolphin.

5.3.4.3 Experience: Adventure Mode

This experience is not customizable because it is already composed by three levels of increasing difficulty. As already said, each level is composed by two parts, *Travel-Flow* (the same as Infinity Mode) and *Treasure Hunt*.

The *Treasure Hunt* phase exploits the same algorithms of the first experience (explore the room) to generate decorations around the room, with an addition. In fact, also the keys (for the first two levels), the password (for the last level) and the treasure chest must be generated. These important elements are generated before the other decorations. In case they can't be spawn due to small dimensions of the room, they are generated near the player, as already said.

If during the *Treasure Hunt* the player can't find the keys or the treasure chest then a vocal command, "Help me", can be used and these important objects will be repositioned near the player. That vocal command would be detected even if it is said by the therapist while the HoloLens are worn by the user patient. This command is particularly useful also for a technical reason, in fact HoloLens is capable to use only quads to represent the floor, therefore if the room has a non-rectangular shape it can happen that some objects are spawned outside it. One of the considered assumptions states that the application should be used in empty rectangular rooms, but even if it is not possible it's not a critical problem because the "Help me" command always allows to bring near the player the important objects thus preserving a good user experience in those situations.

5.3.4.4 Tutorials

The game experiences have been designed and implemented to be as self-explanatory as possible, leveraging a simple UI and intuitive interaction mechanisms. Nevertheless, as already said, some tutorials have been implemented in order to let users get experienced with the rules and the mechanism of catching the rings with the right rotation. Initially it has been added just one tutorial (called "*Tutorial Standard*"), then after the experimentation and thanks to the feedback of the therapists it has been decided to add a second tutorial (called "*Tutorial Basic*") for some users that were having difficulties in completing the first one. In their case this simpler tutorial should work as a transition exercise.

The *tutorial standard* has been implemented to be a particular case of the *Infinity experience*, therefore it has been implemented with a Coroutine function sharing some functionalities with the one used for spawning the flowing elements. The rings keep being spawned with a fixed position until the user gets correctly a certain amount of them (three, in this case).

The *tutorial basic* instead has been implemented a little bit differently, in order to make the users just rotate (and eventually crouch) to collect the elements, without any other additional movements. In this case the generator rotates around the player leveraging a proper Coroutine function and reaching some positions before generating the bubble rings (+45 degrees, -45 degrees, 0 degrees, with respect to the center direction of the player area). The rings have no rotation, they are always generated straight (facing the player). This is the reason why users don't have to move steps but just rotate or crouch to collect them.

For the treasure hunt game, instead, there isn't any tutorial because users have an unlimited amount of time to complete it, and they don't need to learn particular movements since that experience includes more cognitive-related tasks like reasoning, memory and sound orienteering.

5.3.4.5 Additional implementation details of the experiences

Speech Recognition

Speech recognition can be useful for the therapist in some situations because it can allow to trigger some behaviors while is standing near the user patient without wearing the device. A good example is the "*Help me*" vocal command that, as already said, allows to bring important objects of the treasure hunt game near the user patient, in case the therapist considers appropriate to help the patient in completing the experience.

Some other vocal commands can be used by the therapist to move the *Playfield*, pause the game or bring menus near him when he/she can't see them for some reason. In fact, most menus follow the user floating around him/her with a *Tag Along* behavior, while other menus are detached and don't follow the user for comfort reasons, for example when entering the *Explore Room Mode* or when consulting the big menu regarding the statistics of the various trainings. All the vocal commands implemented in the *ATOF* application are in English because, as stated in the design chapter, Italian language is still not supported.

Another important detail that has been noticed is the fact that at the moment speech recognition capabilities decrease considerably when Cortana is activated in the HoloLens settings for online researches. In that case the Speech Recognition lags very often. Deactivating it, instead, the speech recognition is much more performant, therefore this could be a recommended setting. Cortana can be deactivated without problems because speech recognition of the apps isn't affected by that setting.

Sound manager and spatialized effects

All the soundtracks and sounds of the application are managed by a *Sound Manager* class. This class offers some functions capable to dynamically fade in and fade out music during the game, and it is also in charge to play sound effects in the proper situation.

The sound effects are spatialized in order to help users concentrate towards a specific direction, so they can serve as powerful feedbacks. Some examples are represented by the generators of flowing elements, that emit a sound capable to attract the user as good as the visual indicators do.

On top of all those sound effects, there are also low volume soundtracks adorning the application. The soundtrack in some situations is dynamically speeded up by the Sound Manager with a Coroutine. This happens for example during the *Infinity Mode*, when the user takes an X2 powerup that increases the velocity of the flowing elements as well as the soundtrack.

All effects and soundtracks can be deactivated by the therapist from the related settings menu, if necessary, allowing to furtherly customize the application.

Motion sickness

Motion sickness occurs when exposure to a virtual environment causes symptoms similar to general discomfort, disorientation, postural instability and nausea. This is a typical problem of VR experiences. It is caused when there is a misalignment between the movement perceived by the eyesight and the one perceived by the vestibular apparatus. There are some solutions to mitigate this problem, one of which recommends using reference objects anchored to the world.

The problem of the motion sickness in the case of Mixed Reality is quite limited because the user maintains a connection with the world, therefore he/she has got lot of steady reference objects. For the same reasons, the guidelines recommend to use world-anchored UIs.

Motion sickness can be caused also by a low framerate. Considering this point, in the development of the application there have been used some optimization techniques to avoid resources waste. In addition, extra visual effects have been deactivated whenever they caused drops in the framerate during the testing phase.

5.3.5 Vuforia image tracking

As said in the design chapter, there was the need to find a way to track in real-time the position and the rotation of the Smart Dolphin in order to make it possible to collect the flowing objects, especially the bubble rings, in the mixed reality environment. The best option that has been found to implement this behavior is the Vuforia SDK, that uses computer vision technology to recognize and track planar images (Image Targets). In principle it could track also 3D objects, but it is more efficient with 2D images plus the fact that in this application the Smart Object is kept in the hands of the user (covering some portion of the dolphin) therefore Vuforia would haven't been able to recognize the Smart Object in its entirety. For these reasons the 2D image target has been used. The steps to obtain tracking capabilities in HoloLens are described in detail in the *appendix B (9.2)*.

Once everything is configured and the image has been attached to the real object, it is possible to leverage two ways for making the tracking, *simple tracking* or *extended tracking:*

- With the *simple tracking* the object immediately appears and disappears depending on the whether the Vuforia SDK is still recognizing it through the HoloLens embedded RGB camera.
- With the *extended tracking* there is a more deep integration between the Vuforia SDK and the HoloLens Mixed Reality Toolkit, in fact the Vuforia SDK detects the target via HoloLens camera, calculates a pose of the target and then hands this pose off to the HoloLens spatial tracker system; then HoloLens tracks the target and approximately every second Vuforia will attempt to re-detect the target and update the pose for HoloLens.
  In this way, even if the target is lost, the virtual arrow representing the position and rotation of the Smart Dolphin doesn't disappear and is maintained in the mixed reality environment in an heuristic position representing where it was the last time that it was

detected. Of course, this isn't as precise as the *simple tracking* case, and for this application purposes it wasn't even quite necessary, so it has been decided to use the *simple tracking* method.

The process of detecting the Image Target is depicted in Figure 5.10.

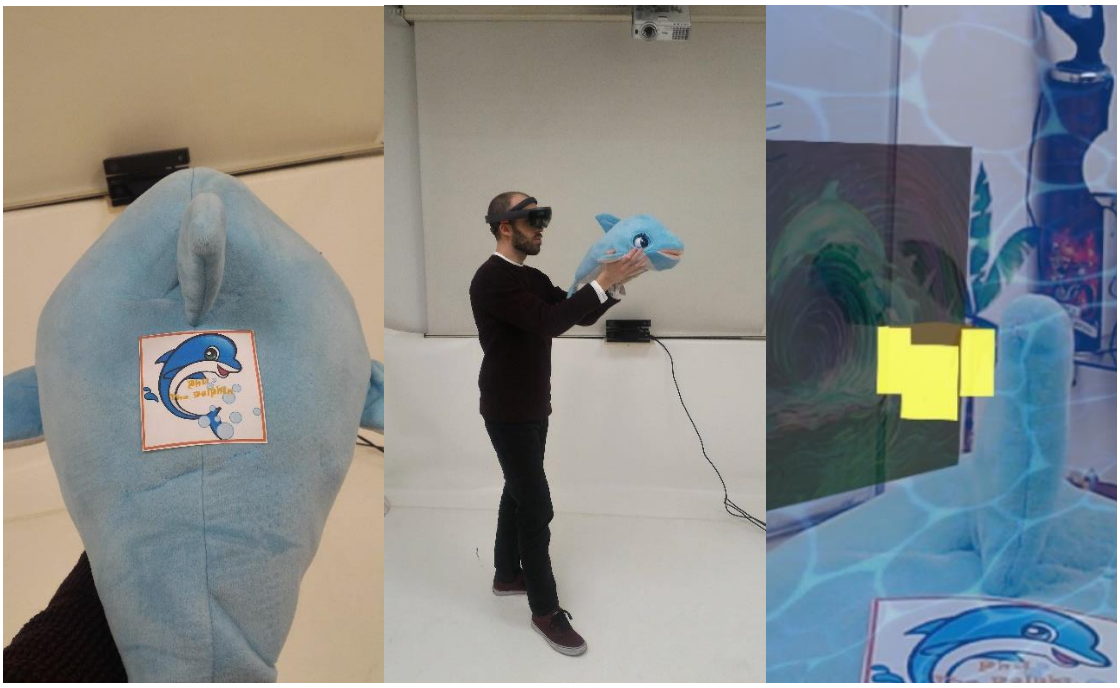


Figure 5.10: 2D image target (left) - detecting target (center) - detected target, yellow arrow appears (right)

A problem encountered while using the Vuforia SDK for HoloLens has been a flickering effect. In principle, Vuforia is capable to do positional and rotational tracking in a very smooth way, but some tweaking was required in this case due to some limits of the Vuforia SDK specific implementation for HoloLens. In fact, unlike how it has been implemented for other platforms, Vuforia SDK for HoloLens introduces some annoying flickering when automatically updating the Image Target position [78]. The update of the rotation of the Image Target instead works well.

The problem has been solved forcing the Image Target to follow the Camera (representing the HoloLens), therefore having the Image Target always relatively close to the last position update. In this way the Vuforia SDK can make a much less effort and less errors in updating the position, allowing a smooth tracking with no flickering at all. This procedure solve completely the flickering problem, at least for the *simple tracking* case, that was the only one case interesting for the *ATOF* application, since the *extended tracking*, using a heuristic position, is less precise.

Another problem faced during the testing of the application has been the incompatibility between Vuforia image tracking and the live streaming. A MRC (Mixed Reality Capture) live preview while Vuforia is running can't be done in any case. In fact, if a Live preview is started while a Vuforia-based app is running on the HoloLens, an error appears in the MRC; if instead a Vuforia-based app is started while a Live preview is running, the app will not start. Therefore, their running is mutually exclusive.

The limitations described above are related to real-time camera access for apps running on the HoloLens. In order to guarantee optimal detection and tracking performance, Vuforia is granted sole access to the live camera feed [79]. This is similar to other platforms that Vuforia supports, such as Android and iOS.

To mitigate that problem, there have been implemented two vocal commands, "*Streaming On",* and "*Streaming Off",* that dynamically deactivate and activate the Vuforia camera in order to allow streaming through the monitor of the notebook. When the Vuforia camera is deactivated an arrow relatively fixed to the HoloLens camera appears, replacing the arrow detected by Vuforia representing the position and rotation of the Smart Object. This mitigation allows also the user to occasionally rest the arms and the hands when he/she is tired of keeping the Smart Dolphin in the field of view of the camera. This physical tiredness could however be a positive thing considered the fact that one of the objectives of the system is to make them do some moderate physical activity.

5.3.6 Data collection and analysis

ATOF saves all the statistics regarding the played matches both for the *Infinity Mode* experience (represented by the *Travel-Flow* game) and for the *Adventure Mode* experience (including the three levels of both the *Travel-Flow* phase and the *Treasure Hunt* phase). In this way the therapists can have a precise idea whether the patient is improving or not and consequently customize the system to suit the user needs.

In order to save the data, there have been used some serializable classes containing all the relevant attributes describing each training. Some examples are the number of rings correctly caught, the maximum error tolerance allowed to catch a ring and the number of obstacles avoided. At the end of each experience, at the discretion of the therapist, all the data is saved using the JSON format. The file obtained, named "*dataMatches.json*", is saved in the folder of the application.

The most important part of the data can be also seen inside the application either in a chronological way or ordered by the best performance. In this way the therapist has the possibility to see the data statistics either inside the application or outside it, directly consulting the JSON file that is accurately delivered by the application with a readable formatting.

The Figure 5.11 shows an example of the JSON containing the data of the matches.

```
{
    "allMatches": [
        {
            "numMatch": 1,
            "dateTime": "3/2/2019 4:20:15 PM",
            "namePlayer": "CHRIS",
            "scorePlayer": 150,
            "gameMode": 1,
            "levels": [
                {
                    "level": 0,
                    "yesRings": 30,
                    "totRings": 60,
                    "rateYesRings": 0.5,
                    "errToleranceRings": 25.0,
                    "avoidedObstacles": 25,
                    "totObstacles": 30,
                    "rateAvoidedObstacles": 0.8,
                    "timeTreasure": 0.0
                }
            ]
        },
        {
            "numMatch": 2,
            "dateTime": "3/2/2019 4:27:30 PM",
            "namePlayer": "TEO",
            "scorePlayer": 200,
            "gameMode": 1,
            "levels": [
                {
                    "level": 0,
                    "yesRings": 40,
                    "totRings": 60,
                    "rateYesRings": 0.66,
                    "errToleranceRings": 25.0,
                    "avoidedObstacles": 30,
                    "totObstacles": 30,
                    "rateAvoidedObstacles": 1.0,
                    "timeTreasure": 0.0
                }
            ]
        }
    ]
}
```


Figure 5.11: JSON example of two Infinity Mode saved matches

5.3.7 Monitoring and feedbacks

Monitoring and feedbacks are important requirements for the therapist because they allow to constantly observe the user patient in order to understand and analyze his/her reactions depending on what it happens inside the mixed reality environment. With monitoring it can be observed what the user is doing from his/her point of view, and with feedbacks we have another measure to determine the effectiveness of the training.

For the monitoring functionality it has been preferred to simply leverage the new "*Microsoft HoloLens*" UWP application. It is an app that can be downloaded and installed on any Pc directly from the Microsoft Store. It requires the HoloLens, and it provides various functionalities for the device, one of which allows to stream on the notebook/Pc display what the user is currently seeing. Sometimes there can be some difficulties in streaming the content principally due to connection problems. An alternative is the *Windows Device Portal*, a local website providing even more functionalities and settings for the HoloLens device. Unfortunately, the streaming in the *Windows Device Portal* works way slower compared to the *Microsoft HoloLens* application.

The feedbacks instead are given principally by the leds placed inside the *Smart Dolphin* that indicate whether an action has been well performed. In addition, the different spatialized sounds integrated in the game enhance those feedbacks. In this way the therapist, also in the moments when he/she isn't seeing the streaming on the pc (because maybe the patient needs some help), can know how well the training is going just observing these feedbacks represented by led lights and sounds.

6 Exploratory empirical study

In this chapter the focus we discuss the exploratory empirical study done at the day-care centre "*Fraternità e Amicizia Soc. COOP UNLUS"*, a non-profit organization that helps people with disabilities.

6.1 Research design

Objectives of the evaluation

The purpose of the assessment was to evaluate the following parameters:

- **Likability:** a measure indicating how much the app has been liked
- **Usability:** a measure for acceptability and ease of use of the application

To assess those two parameters of the *ATOF* application, two days of experimentation were organized. Data about those parameters was collected on the second day.

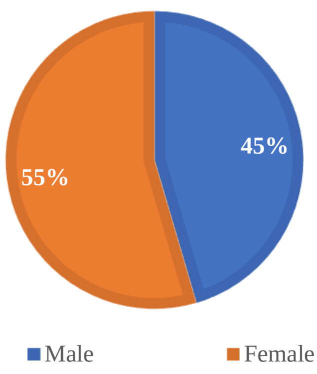
Participants profile

The users chosen to assess the application were 14 in total, although in the second experimentation day only 11 were present. Each user-patient had a different impairment. The sample of patients considered for the test presented the following properties.

The *gender distribution* is described in Table 6.1 and Graph 6.1. There was a slight prevalence of females.

	Frequency	Rate
Male	5	45,5
Female	6	54,5
Total	11	100,0

Table 6.1: gender distribution of the sample

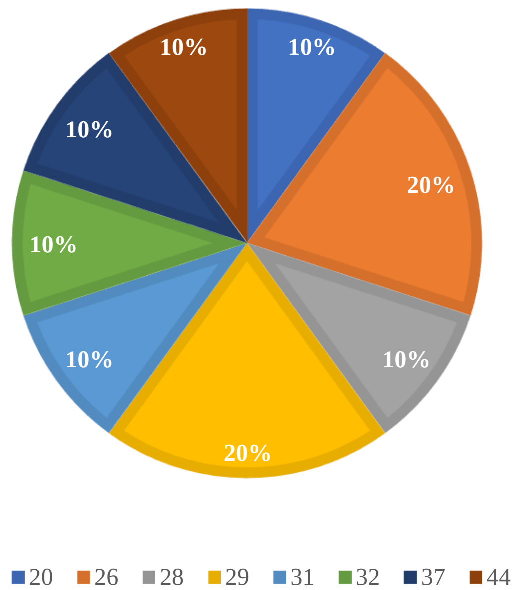


Graph 6.1: gender distribution of the sample

The *age distribution* of the sample is represented in Table 6.2 and Graph 6.2. The average age of the considered sample was 30 years old, with a standard deviation of approximately 6 years. The youngest participant had 20 years old while the oldest had 44 years old.

Valid participants	11
Missing	0
Average age	30,09
Std. deviation.	6,236
Minimum	20
Maximum	44

Table 6.2: age distribution of the sample

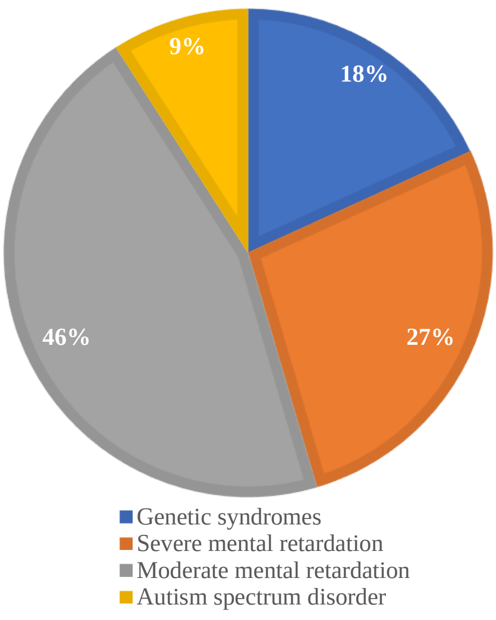


Graph 6.2: age distribution of the sample

The *diagnosis distribution* of the sample is depicted in Graph 6.3. There was a prevalence of subjects having a moderate mental retardation diagnosis. The frequencies of each diagnosis are reported in Table 6.3.

Diagnosis	Frequency	Rate
Genetic syndromes	2	18,2
Severe mental retardation	3	27,3
Moderate mental retardation	5	45,5
Autism spectrum disorder	1	9,1
Total	11	100,0

Table 6.3: diagnosis distribution of the sample



Graph 6.3: diagnosis distribution of the sample

6.2 Context

The exploratory empirical study was done at *Fraternità e Amicizia (F&A) Coop Soc ONLUS*, that is a non-profit organization association in Milan working with disabled people of different ages. *F&A* supports disabled people, with the aim to empower, maintain, rehabilitate or qualify psycho-operative competences or motor, manual and cognitive functions, without neglecting each person's past as well as relational and social aspects of every patient. Therefore, in parallel with traditional learning, the association promotes activities able to stimulate each individual's emotional world through verbal, painting, graphical and musical activities to help these people build their own personalities.

Experimentations settings and setup

In order to make the experimentations, for both days it was necessary to previously set up all the different required components of the application:

- **HoloLens**
- **Dolphin Smart Object**
- **Router**: to connect all the devices in a LAN
- **Notebook**: to manage the server allowing the communication between HoloLens and the Smart Object, and to stream what the users were seeing through the *Microsoft HoloLens* dedicated application. In alternative, the Windows Device Portal could be used although slower.

First, all the three devices (HoloLens, Smart Dolphin, Notebook) were connected to the dedicated router. Then, to configure the Smart Dolphin to send its events to the intermediate server, an HTTP POST request was sent to the Smart Toy to change its target. The target is basically the IP number to which the Smart Dolphin sends its events. For this passage it was used *Postman* [65] (a practical tool for testing APIs). The *default* target of the Smart Dolphin can be changed to have already set the IP of the intermediate server (in that case this step can be skipped). In Figure 6.1 it can be seen the HTTP request sent to the Smart Dolphin.

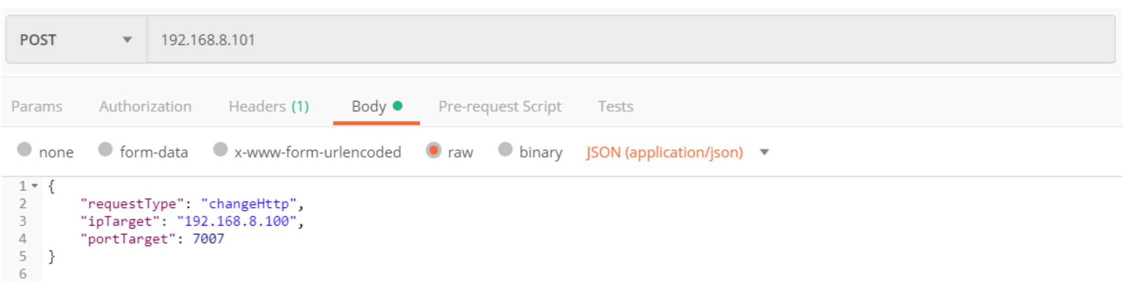


Figure 6.1: HTTP post request sent to the SmartToy to change its target. In the "ipTarget" should be placed the intermediate server.

After this, both the intermediate server and the *ATOF* application were started. To allow streaming it is needed to deactivate Vuforia because it goes in conflict with the Microsoft HoloLens streaming application, as said in the implementation chapter. In fact, both Vuforia and the HoloLens application try to use the device camera exclusively, therefore it is not possible to use them at the same time. So, to dynamically deactivate Vuforia and allow streaming, the vocal command “Streaming On” was used.

After deactivating Vuforia, the Microsoft HoloLens application was used to stream the content so that other people present in the room could see what the user patient was doing.

The app is structured in a flexible way, in fact it doesn’t necessarily need the Smart Dolphin or the router to work. This reduces significantly the setup time, in case the game is played without the Smart Object. In that case the virtual arrow representing the position of the Smart Dolphin (tracked by Vuforia) is replaced by an arrow representing the position of the HoloLens camera. For more details see the relative section discussing the app implementation. Anyway, for the purposes of the experimentation, all the devices were needed.

To avoid any problems regarding battery charge of the HoloLens, a power bank with a 1-meter usb cable was used. This solution worked well, was well-accepted with no problems and, plus, engaged the users, that thought they were famous singers wearing batteries during a performance. In Figure 6.2 can be seen the experimentation equipment.

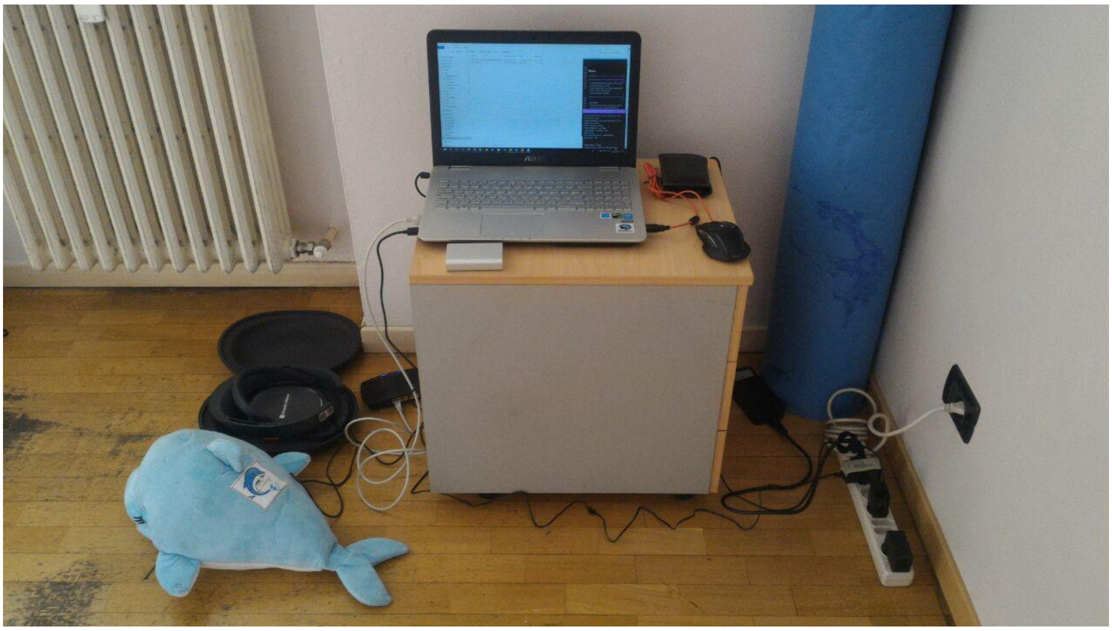


Figure 6.2: experimentations setup

Data collection instrument

The instrument used for gathering the data regarding likability and usability was a survey reported in Table 6.4 and Table 6.5. It has been administered in Italian language, although in this document it is reported in English.

SURVEY: Likability Scale	
# Item	**Question (answer values 1-7)**
Item 1	*How much did you like the game?*
Item 2	*Is the game beautiful?*
Item 3	*Is the dolphin unpleasant?*
Item 4	*Is the game funny?*
Item 5	*Is it annoying to play with the bubble rings?*
Item 6	*How much did you enjoy the activity?*
Item 7	*Is it beautiful the sea environment you saw?*
Item 8	*Was the exercise annoying?*
Item 9	*Would you enjoy other games with the mixed reality device?*
Item 10	*Was the game engaging?*

Table 6.4: Likability scale (survey)

SURVEY: Usability Scale	
# Item	**Question (answer values 1-7)**
Item 1	*How much easy was the game for you?*
Item 2	*Is it comfortable to wear the device?*
Item 3	*Is it easy to keep the dolphin in the hands?*
Item 4	*Is it funny to play with both the dolphin and the device at the same time?*
Item 5	*Is it annoying to keep the device on the head?*
Item 6	*Did you see well what was projected by the device?*
Item 7	*Was it clear what you had to do?*
Item 8	*Was it simple to understand where the aura was?*
Item 9	*Was it simple to find the indicated objects?*
Item 10	*Was the game too tiring?*

Table 6.5: Usability scale (survey)

6.3 Study execution

6.3.1 Day one

The experimentation setting was a small gym, an empty room of approximately 5*4 meters. This dimension was optimal for the purposes of the application, in fact the device mapped it very precisely, allowing to generate various decorations both on the floor and walls. A mirror was present in the room but it was covered to avoid possible mapping problems.

After configuring everything, with the help of the educator, all the users were gathered in the same room. In fact, before letting them use the application, there was the need to show them a demonstration in order to help them understand the mechanics of the game and what to do.

The experience was organized in two phases:

- Exploration of the room
- Standard tutorial of the game

Exploration of the room

Each one of the users explored the room mapped and completely transformed into an ocean floor decorated with sand, corals, rocks, fishes and other thematic things. Leveraging an HTTP POST call sent with *Postman,* a command was used to change randomly the decorations and to start the animation of the rising water along with the seagulls flying around the center of the room. The aim of changing the decorations for all the users was to let them imagine they had a personal room.

Users could also interact with decorations (fishes, wales, jellyfish and more) attached to the walls. In fact, those decorations start to move when approaching them, and freeze when the player is far.

This phase gave some excitement to the users. For example one of them, seeing an octopus moving animatedly on a wall, started to dance trying to mimic its movements. This excitement has been emphasized also by the fact that the other people were seeing from the notebook what the user was seeing through HoloLens, making them more participative.

Standard tutorial

After the exploration of the room, each one of the users was invited to play the standard tutorial. In this tutorial, as said, the player must get three centered rings, three rings rotated a bit to the right and other three rings rotated a bit to the left.

The bubble rings are being generated until the player gets them with the correct rotation angle. With this approach the users had the opportunity to try multiple times to learn how to move correctly to get the rings, thus having satisfaction when they succeeded.

It was noticed that this exercise is simple to understand for most users and, during it, some of them in a few minutes improved a bit in moving properly, standing more straight with the back and the head.

A consistent part of the group (approximately the 60%) succeeded in completing the tutorial, while the other part got some rings correctly and then were unable to continue.

It was noticed that those who didn't succeed found difficult to move and rotate themselves in a proper way. Even if the game tutorial requires very basic skills, it was thought that would have been a good idea to develop an even simpler tutorial exercise. Then, once completed, those users could probably benefit even more from the standard tutorial exercise.

In fact, as seen in the implementation chapter, in the standard tutorial the generator doesn't move, and the rings are spawned with a certain amount of rotation implying that the player should both rotate and move itself a bit in space (generally just one step) to accomplish the task properly.

Streaming distracting some users while training

It was noticed a little problem during the Game Tutorial. Streaming the HoloLens content on the notebook display influenced a few users that, instead of looking through the HoloLens lenses to complete the game, were looking towards the notebook display most of the time.

In addition, the visualization on the streaming app is delayed by some seconds with respect to the device. The suspect is that this could add some problems to some NDD users.

The streaming was activated in order to have a more festive, relaxed and participative atmosphere in the room, but this distraction, even if very mild, it is indeed an element to consider.

As a solution, it could be better to let the other fellows see what the current user is seeing, and at the same time prevent the current user from seeing the notebook display positioning it in a proper way. For example, all the users could stay behind the notebook, and the player could stay in front of it, facing its rear. But this solution to work well would require a quite larger room if all users are required to stay all together inside it.

Overall comment about the preparatory experimentation

From the positive comments it has been deduced that the experimentation was useful and entertaining both for users and therapists. It was perceptible the interest from the users in the game and this allowed both to entertain them and test the application at the same time. Some users asked to play a second time and those requests were fulfilled although the time was over. Some users said they felt like they were in an alternative funny world transported to their gym.

All the users seemed to tolerate well the device and the fact they didn't lose contact with the reality could helped some of them in not getting confused or scared.

In this first preparatory experimentation, it wasn't collected any specific data about likability and usability of the application.

6.3.2 Collecting feedback as new requirements

With the feedback of the educator it has been thought that a simpler second tutorial could have been structured in a way where the user is standing as usual at the center of the *Aura*, and has just to rotate himself/herself towards the direction of the generator which sometimes moves around the player and then spawns rings always perpendicular to him/her.

In detail, the new requirements extracted from educator's feedback were:

- The generator (the "spherical energy ball" from which the rings are created) should have the capability to rotate around the player area.
- The generator this time should spawn only straight rings perpendicular to the player area where the user stays.
- The generator should move also a bit down, in a way that the player has to crouch to collect rings, making the tutorial a bit more challenging.

The design choices that emerged by considering these requirements brought to create the *Tutorial Basic* already described in both the design and implementation chapters.

The implementation of this new tutorial has been made between the two days of experimentation, in order to have the possibility to test it with NDD users.

6.3.3 Day two

For the second day of experimentation the small gym of the building was chosen again thanks to its ideal room dimensions. In this second day it was planned the collection of surveys about *likability* and *usability*.

After having completed the setup of all the devices all the **11 users** (3 of them were absent) were gathered in the room in order to start the experimentation.

Due to the fact that in the first experimentation they already had explored the transformed room, this second day was entirely planned to let them try the newly added simpler tutorial along with the standard one.

Tutorial basic version

Each one of the users played the new basic game tutorial added as a consequence of the feedback gathering. In particular, the NDD users had to get one ring coming from the center, one ring coming from the right (after the generator rotated reaching +45 degrees), and one ring coming from the left (after the generator rotated reaching -45 degrees). Finally, the generator came back to 0 degrees rotation and went a bit down, inviting the users to get the last ring while crouching or sitting in the floor. The educator explained that this approach allows to act on two different physical levels, the first one when the users need to stand, and the second one when they have to crouch. The bubble rings also in this case were being generated until the player was catching them with the correct rotation angle.

It was noticed that this exercise was way simpler to accomplish for them, as expected. In fact, all users of the group succeeded in completing the tutorial. However, just some users completed it almost straight away (approximately the 60%).

This experimentation showed that, for some users, this basic tutorial exercise could be the ideal start point. Then, when this exercise is mastered, they could pass to the standard tutorial exercise, that is a bit more challenging. Instead, for the users that immediately completed this basic exercise, the suggestion is that they could directly start with the standard tutorial.

Bonus exercise – Real match with rings and obstacles

Some of the users requested to play another time. Their requests were fulfilled, also because the basic tutorial was probably too simple for them. For those users a custom real match was prepared, using the *Infinity mode* and including obstacles to avoid (a plastic can and a broken bottle). Another challenge that the *Infinity Mode* added was the fact that the player while is avoiding obstacles cannot leave the aura for more than 10 seconds, otherwise the health starts decreasing.

Those users understood what they had to do and completed the game, although some of them completed it more quickly than the others.

One of them even wanted to try playing with sharks, that implied a more difficult challenge, because they are obstacles mildly following the player.

Overall comment about the second experimentation

Those two experimentations days have been a good opportunity to test the application *likability* and *usability*.

It was observed interest from most of the users also about the second basic tutorial exercise. Some of them wanted to try different tasks of the app and this could confirm that an application customizable depending on the user is a good way to go, especially for users with impairments.

The observations suggest that HoloLens can be a good way to create new type of experiences for NDD people, and those games can hide exercises that improve their condition while entertaining them.

For this second experimentation day the survey was prepared to collect all the data regarding *likability* and *usability*. At the end of the exercise each user filled and submitted the form using a tablet. Then the data has been analysed. In the next paragraph the results are reported.

6.4 Results

At the end of the experimentation, 11 out of 14 participants filled out the *Likability* and *Usability* surveys regarding the test done.

6.4.1 Likability results

The results regarding the *Likability* parameter are reported in Table 6.6. The items represent the different questions that the users had to answer through the survey. For each of those questions the scale was between 1 and 7, where 1 means “not much” and 7 means “very much”.

Likability Statistics

		item 1	item 2	item 3	item 4	item 5	item 6	item 7	item 8	item 9	item 10
N	Valid	11	11	11	11	11	11	11	11	11	11
	Missing	0	0	0	0	0	0	0	0	0	0
Trend		7	7	1	7	1	7	7	1	7	7
Minimum		4	4	1	4	1	6	1	1	1	4
Maximum		7	7	7	7	6	7	7	7	7	7

Table 6.6: Likability statistics

The questions of the *likability* part of the survey were:

- **Item 1:** *How much did you like the game?* (scale 1-7, best case: 7)
- **Item 2:** *Is the game beautiful?* (scale 1-7, best case: 7)
- **Item 3:** *Is the dolphin unpleasant?* (scale 1-7, best case: 1)
- **Item 4:** *Is the game funny?* (scale 1-7, best case: 7)
- **Item 5:** *Is it annoying to play with the bubble rings?* (scale 1-7, best case: 1)
- **Item 6:** *How much did you enjoy the activity?* (scale 1-7, best case: 7)
- **Item 7:** *Is it beautiful the sea environment you saw?* (scale 1-7, best case: 7)
- **Item 8:** *Was the exercise annoying?* (scale 1-7, best case: 1)
- **Item 9:** *Would you enjoy other games with the mixed reality device?* (scale 1-7, best case: 7)
- **Item 10:** *Was the game engaging?* (scale 1-7, best case: 7)

It can be noticed that the questions 3,5 and 8 were given in an inverted style, therefore the best possible answer to receive was 1.

It can be observed that there is a very good trend for all the questions regarding the *likability* of the *ATOF* application.

6.4.2 Usability results

The results regarding the *Likability* parameter are reported in Table 6.7. The items represent the different questions that the users had to answer through the survey. For each of those questions the scale was between 1 and 7, where 1 means "not much" and 7 means "very much".

Usability statistics

		item 1	item 2	item 3	item 4	item 5	item 6	item 7	item 8	item 9	item 10
N	Valid	11	11	11	11	11	11	11	11	11	11
	Missing	0	0	0	0	0	0	0	0	0	0
Trend		7	7	7	7	1	7	6	4[a]	7	1
Interval		5	6	5	3	5	4	3	6	5	5
Minimum		2	1	2	4	1	3	4	1	2	1
Maximum		7	7	7	7	6	7	7	7	7	6

a. More trends exist. It is visualized the smallest value (see item 8)

Table 6.7: Usability statistics

The questions of the *usability* part of the survey were:

- **Item 1:** *How much easy was the game for you?* (scale 1-7, best case: 7)
- **Item 2:** *Is it comfortable to wear the device?* (scale 1-7, best case: 7)
- **Item 3:** *Is it easy to keep the dolphin in the hands?* (scale 1-7, best case: 7)
- **Item 4:** *Is it funny to play with both the dolphin and the device at the same time?* (scale 1-7, best case: 7)
- **Item 5:** *Is it annoying to keep the device on the head?* (scale 1-7, best case: 1)
- **Item 6:** *Did you see well what was projected by the device?* (scale 1-7, best case:7)
- **Item 7:** *Was it clear what you had to do?* (scale 1-7, best case: 7)
- **Item 8:** *Was it simple to understand where the aura was?* (scale 1-7, best case: 7)
- **Item 9:** *Was it simple to find the indicated objects?* (scale 1-7, best case: 7)
- **Item 10:** *Was the game too tiring?* (scale 1-7, best case: 1)

It can be noticed that the questions 5 and 10 were given in an inverted style, therefore the best possible answer to receive was 1.

It can be observed that there is a very good trend for almost all the questions regarding the *usability* of the *ATOF* application. Answers to question 7 (regarding clarity) and 8 (ease in finding the aura) presented a slightly less good trend value.

6.4.3 Discussion

The results of this exploratory empirical study can't be generalized due to the limited training done with the considered users sample, therefore the study doesn't offer any rigorous evidence of the benefits that *ATOF* tasks, and the *TMR* interaction paradigm, could bring to people with NDD. Furthermore, the heterogeneity of the participants in terms of age and diagnosis makes it more difficult to properly analyze the results. Nevertheless, the specialists gave a very positive opinion on the potential of this innovative paradigm to improve motor and cognitive capabilities.

It hasn't been possible to do an additional inferential analysis of the data, just a descriptive analysis of them. The Cronbach's alpha, a statistical index used in psychometric tests to measure their reliability [30], indicated that the scales were not standardized, therefore not much reliable over time. However, the Cronbach's alpha of the *usability* test was very close to a high value of reliability (optimal values are ideally > 0.70).

The descriptive analysis of the tests presents very good results. It can be concluded that the *ATOF* application has been appreciated by the users and that it has been comfortable to use.

Lesson 1: Target Group

The results of the exploratory empirical study indicate that, during the experience, the participants having a diagnosis of severe mental impairments required in average more support by the therapists than people of other groups. However, also some of these subjects succeeded in completing the tasks, hinting that there is room of improvement. This suggests that, in principle, TMR applications might be more useful for people with a moderate severity level of NDD, since they can better master the interaction mechanisms of the tasks (confirming what experienced in other studies [26][27][28][42]). However, it also suggests that this innovative paradigm, leveraging a more natural interaction, might improve some abilities also in the case of NDD subjects with more severe impairments.

Lesson 2: Customization

The potential value of a system for the NDD field is strongly related to its ability to be customized to suit users' unique needs. In the *ATOF* application this requirement led the design of the experiences during all the development cycle. Tasks should be designed so that adjusting the proper parameters it is possible to obtain multiple configurations adapted to each user. As a result, this can greatly increase the *likability* and *usability* of the system. All these functionalities should be integrated and exposed in a simple user interface allowing therapists to autonomously personalize the application and save the necessary data of the user interaction in order to monitor the patients' progress over time.

Lesson 3: Shared Experience

The sessions of use of *ATOF* were performed as shared experiences, so that both therapists and the other fellows affected by NDD were visualizing on an external display screen what the user was seeing during the experience. This setting enabled the therapist to provide assistance to the user-patient when needed. The NDD user enjoying the experience should not look at the screen to avoid possible distractions, therefore the display should be placed properly in the environment. On the other hand, the other NDD people can enjoy what happens in the TMR environment even if they do not wear the headset. They could feel engaged in a shared experience, offer suggestions, and learn from the current user's interactions. Moreover, the tangible feedbacks of the Smart Object can be directly perceived, making the shared experience more involving. The physical presence of other people different from the therapist might also bring benefits to the user, that could feel more relaxed, avoiding risks of self-isolation and maintaining the perception of the surrounding physical space.

7 Conclusion and future work

The novelty of this thesis is the exploration and assessment of the *Tangible Mixed Reality (TMR)* potential to help people affected by NDD, leveraging the interaction between *Mixed Reality* devices and *Smart Objects* with tangible feedbacks. A thorough search of the relevant literature yielded that this is the first case in which the innovative *TMR* interaction paradigm is applied to the NDD field.

The author believes that *Along the Oceanic Flow (ATOF)*, the application instantiated from this paradigm, has a good potential as a supporting tool for existing therapies for people with neurodevelopmental disorders, thanks to the feedback given by the patients and their therapists. The system went through an iterative development cycle, in fact after analysing the requirements, designing and prototyping the system, an empirical evaluation led to a redefinition of some requirements and design choices considering therapists' suggestions in order to suit the users' needs as much as possible.

During the work, several technical and methodological challenges were faced, mainly due to the experimental technology involved, but also because of the limited number of documented examples of HoloLens applications and their underlying design solutions, as well as the limited number of publications concerning the usage of *Mixed Reality* among people with NDD and similar disabilities.

The analysis of the *likability* and *usability* parameters assessed during the exploratory empirical study gives an encouraging result, therefore this research could have good motivations to be furtherly explored.

The author is confident that some of the design solutions, the problems encountered and the solutions found, could be inspirational for the designers of wearable *TMR* applications dedicated to people with NDD as well as other users groups with different forms of intellectual disabilities.

Regarding the future works, there are some points that could be considered to continue the research.

From a design and technological perspective, there could be created new experiences. An example could consider adding new interactions with the Smart Dolphin introducing a conversational approach with the NDD user in order to improve social skills, when HoloLens will support Italian language recognition. More complicated experiences that can be added could leverage the usage of two HoloLens coupled with two different Smart Objects so that the users should cooperate to solve puzzles in the *Treasure Hunt* exercise.

Regarding the possible improvements of the current application, the streaming problem will be solved as soon as Microsoft will fix the issues related to the dedicated streaming application. Similarly, the usage of an intermediate server could be avoided when Microsoft will introduce more functional web-server capabilities for the HoloLens.

A more long-term future work is related to the need of both a stronger assessment of the features already tested in the current study, and the evaluation of the benefits of *ATOF* for people with NDD to improve motor and cognitive skills. The latter issue would require an articulated controller study, for a period of at least six months, in order to compare the effects of interventions based on *ATOF* with more traditional forms of treatment. Rigorously controlled studies in the NDD field are very complex due to the heterogeneity of the impairments associated with NDD, the difficulty of recruiting a sufficiently large sample of "homogeneous" subjects, and the need to take into account many variables.

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9 Appendix

In this section some extra documents are attached.

APPENDIX A integrates a short guide to correctly setup the *ATOF* system having the full hardware equipment.

APPENDIX B encloses a short guide, step by step, to correctly configure Vuforia for HoloLens and some suggestions to obtain the best performance.

APPENDIX C reports the certificates obtained by the author through the successful completion of some AR and VR courses.

9.1 APPENDIX A - ATOF setup guide

Steps to configure *ATOF* to work with the *full hardware equipment*.

Full Hardware Equipment: *HoloLens, Smart Toy, Notebook, Router*	
Functionalities: full interaction between the HoloLens and the Smart Toy (touch events, feedback leds, mouth and eyes movement); monitoring capabilities	
# Step	**Instruction**
1	Plug the dedicated configured router into a power outlet
2	Connect HoloLens and Notebook to the Wi-Fi.
3	Turn on the Smart Dolphin. It will connect automatically to the Wi-Fi
4	Start the server on the notebook, double clicking “Server.py”
5	Turn on the HoloLens and start the *Along the Oceanic Flow* application.
6 (opt)	If monitoring through the notebook is needed, say “Streaming On”. This will deactivate Vuforia and will replace the tracking of the Smart Toy with the tracking of the head (this step can be used also to rest during the training). Then open the official streaming application. To stop monitoring, close the streaming application and say “Streaming Off”. This will also reactivate Vuforia therefore the tracking of the Smart Dolphin.

Table 9.1 ATOF setup guide

Removing the router and the notebook the app will still run, but monitoring functionalities and interactions (except the real time tracking) will be lost.

9.2 APPENDIX B – Vuforia for HoloLens

Required steps to obtain tracking capabilities for 2D images in HoloLens.

Vuforia – Steps to obtain tracking capabilities in HoloLens	
# Step	**Instruction**
1	A 2D image needs to be created by the developer. This image should follow some requirements to obtain a good tracking, it should be rich in details, have good contrast and no repetitive patterns. This is because Image Targets are detected based on natural features extracted from the target image and then compared at run time with features in the live camera image of the Hololens.
2	When the 2D image has been created, the developer needs to upload it on the Vuforia website (in the personal area). A star rating is assigned to the image, and it ranges between 1 and 5 stars depending on the quality of its tracking capabilities.
3	Then from the Vuforia website it can be downloaded a Unity package, that later can be imported in Unity, containing all the image targets that we want to track in the application.
4	The Vuforia SDK needs to be imported and configured in the Unity project. Moreover, a special set of behaviors provided by the Vuforia SDK need to be added to the Mixed Reality Camera and customized to allow tracking capabilities.
5	At this point, the Unity package containing the Image Targets can be added to the project, and an element representing the 2D image that the developer wants to track can be added in the project hierarchy. One of the scripts that should be attached to this Image Target object is a TrackableEventHandler that allows to specify some actions whenever the target is detected or lost. In the *ATOF* app it has been made appear a simple arrow in order to let the user know more precisely how he/she is moving and rotating the Smart Dolphin inside the mixed reality world. To this image target it has also been added a collider to detect collisions with the other virtual objects (like the rings) and through this mechanism it is compared the rotation of the dolphin with the rotation of each ring, thus deciding if the user has taken the ring correctly or not.
6	Finally, the 2D image can be attached to the real object whose tracking is needed. In the *ATOF* app it has been attached on the back of the dolphin. It should be preferable to keep the Image Target as perpendicular as possible with respect to the HoloLens camera, avoiding reflections, therefore some stratagems could be studied to improve the tracking. Nevertheless, Vuforia is capable to perform a quite good tracking even without having optimal conditions.

Table 9.2: Steps to obtain tracking capabilities in Hololens

9.3 APPENDIX C – Certificates AR and VR courses

In this appendix are reported the certificates of attendance obtained through successful completion of the courses:

Forge-Reply: Augmented Reality (23 november 2018)

Forge-Reply: Virtual Reality (17 december 2018)

organized by *Fastweb Digital Academy* at the *Cariplo Factory Lab*, in Milan.

Dettagli destinatario

Nome	Christian Tagliabue

Dettagli di chi rilascia il badge

Nome di chi rilascia il badge	Fastweb Digital Academy

Dettagli badge

Nome	Augmented Reality - Partecipazione e Profitto
Descrizione	Si certifica che lo studente ha frequentato con profitto presso Fastweb Digital Academy il corso Forge-Reply: Augmented Reality
Corso	Augmented Reality.nov
Criteri	Gli utenti conseguono il badge al soddisfacimento dei requisti elencati: • Il badge viene conseguito se il ruolo seguente lo rilascia: ◦ Manager

Dettagli destinatario

Nome	Christian Tagliabue

Dettagli di chi rilascia il badge

Nome di chi rilascia il badge	Fastweb Digital Acaemy

Dettagli badge

Nome	Virtual Reality dic18- Partecipazione
Descrizione	Si certifica che lo studente ha partecipato presso Fastweb Digital Academy al corso Forge-Reply: Virtual Reality. Competenze acquisite: -Utilizzo dell'editor di Unity 3D -Concetti base della grafica 3D -Concetti generali di realtà virtuale -Flusso di lavoro completo dall'ideazione alla build finale di un'applicazione VR
Corso	Virtual Reality.dic
Criteri	Gli utenti conseguono il badge al soddisfacimento dei requisti elencati: • Il badge viene conseguito se il ruolo seguente lo rilascia: ◦ Manager